



Next Generation Network Routing and Control Plane

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Next Generation Network Routing and Control Plane

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February 2011



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Abstract

Concerning the high performance, QoS supported transport services, it is not sufficient that only the traffic transport under a single domain or Autonomous System (AS) is under the consideration. Inter-domain QoS routing is also in a great need. As there has been empirically and theoretically proved, the dominating Border Gateway Protocol (BGP) cannot address all the issues that in inter-domain QoS routing. Thus a new protocol or network architecture has to be developed to be able to carry the inter-domain traffic with the QoS and TE consideration. Moreover, the current network control also lacks the ability to cooperate between different domains and operators. The emergence of label switching transport technology such as of Multi-Protocol Label Switching (MPLS) or Generalized MPLS (GMPLS) supports the traffic transport in a finer granularity and more dedicated end-to-end Quality of Service classes. Under the NGN context, there are plenty of proposals intending to accommodate the issues listed above. Path Computation Elements (PCE) proposed by IETF designs suitable network architecture that aiming at compute the QoS based paths for traffic transportation through intra- and inter-domain. It is a routing component that flexibly supports path computation with different requirements, constraints and areas. It is also can be seen as part of

NGN transport control plane, which integrates with the other functions. In the aspect of resource control, an NGN release Resource and Admission Control Functions (RACF) provides the platform that enables cooperation and ubiquitous integration between networks.

In this paper, we investigate in the network architecture, protocols and algorithms for inter-domain QoS routing and traffic engineering. The PCE based inter-domain routing architecture is enhanced with Domain Path Vector based protocol that compute the domain level path dynamically for the further inter-domain path routing mechanism Backward Recursive Path Computation (BRPC). Furthermore, several algorithms are proposed to compute the domain-level path under more than one constrains (multi-constrains). It is shown by the simulation and analysis that the proposed DPV enhanced PCE inter-domain routing architecture improves the performance of BRPC mechanism in terms of reducing the blocking probabilities and increasing the network inter-domain link utilization. The proposed algorithms enable the PCE compute the domain level path with optimized multiple constrains.

Resume

Der er stort behov for Quality of Service (QoS)-baseret inter-domain rutning. Som, det er blevet bevist, både empirist og teoretisk, er Border Gateway Protocol (BGP) standarden ude af stand til at håndtere alle de problemstillinger, som inter-domæne QoS rutning indebærer. Det er derfor nødvendigt at udvikle en ny netværksarkitektur med en tilhørende protokol, som er i stand til at transportere inter-domænetrafik under hensyntagen til QoS og trafikplanlægning. Det nyværende netværk mangler desuden mekanismer til at muliggøre samarbejde mellem forskellige domæner eller netværksoperatører. Transportteknologier, som benytter labelswitching, så som Multi-Protocol Label Switching (MPLS) eller Generalized MPLS (GMPLS) understøtter datatransport med finere granualitet og mere dedikerede end-to-end QoS klasser. Inden for emnet Next Generation Networks (NGN), er der flere forslag som søger at tilgodese de ovenstående problemstillinger. Path Computation Elements (PCE), forslået af IETF, understøtter fleksible netværksarkitekturer som søger at udregne QoS-baserede ruter for både intra-domæne- og inter-domænetrafik. Det er en

rutningskomponent, som fleksibelt understøtter ruteudregninger med varierende krav, begrænsninger og områdeafgrænsninger.

I denne afhandling undersøges netværksarkitekturer, protokoller og algoritmer for inter-domæne QoS-rutning og trafikplanlægning. Den PCE-baserede inter-domæne rutningsarkitektur udvides med en Domain Path Vector-baseret protokol, som dynamisk udregner rutningen på domæne niveau, som herefter benyttes til den videre inter-domænerutning via Back Recursive Path Computation (BRPS). Herudover fremlægges flere algoritmer til at beregne rutningen på domæne-niveau under flere end én begrænsning (multi-constraints). Det vises gennem simulering og analyse at den foreslåede DPV-udvidede PCE-arkitektur til inter-domænerutning forbedrer ydelsen af BRPC-mekanismen i form af mindre blokeringssandsynlighed og større udnyttelse af netværkets inter-domæneforbindelser. Den foreslåede algoritme gør det muligt for PCE'erne at beregne rutningen på domæne-niveau med optimerede multiple begrænsninger.

Acknowledgements

This is a great feeling that I would like to share with my parents, friends, and all the colleagues.

Specially, I want to thank my supervisor Michael for his great inspiration and help. During these three years PhD study, he guided me into the world of academic and showed me the ways to make the adventure in my work. I always got encouraged by talking with him when I met with troubles during my research. I also appreciate the help and cooperation I got from all my colleagues in DTU Fotonik networking group. The time my colleagues have spent in reviewing my papers and thesis is really appreciated. Finally I would like to thank to Anders's kindly help with the translation of the abstract part.

Ph.D Publications

Publications as first author in the area of Next Generation Network control plane, Carrier Ethernet test bed and PCE based inter-domain routing:

Carrier ethernet network control plane based on the Next Generation Network

Fu, Rong ; Wang, Yanmeng ; Berger, Michael Stubert

2008 First ITU-T Kaleidoscope Academic Conference - Innovations in NGN: Future Network and Services

Next Generation Network based Carrier Ethernet test bed for IPTV traffic

Rong Fu, Michael S Berger, Yu Zheng, Lukasz Brewka, Henrik Wessing
EUROCON 2009, EUROCON '09. IEEE

Domain Vector Approach to PCE Based Inter-domain Routing

Rong Fu, Michael S Berger

IEEE INFOCOM 2010 student workshop held in conjunction with
INFOCOM March 14, 2010, San Diego, CA

Enhanced BRPC Routing Procedure for PCE based Inter-domain Routing

Rong Fu, Jiang Zhang, Michael Berger

ICCOM'10 Proceedings of the 14th WSEAS international conference on Communications

Domain Path Vector Routing Mechanism for Computing Inter-Domain Traffic Engineering Label Switch Paths

Rong Fu, Michael S Berger

OPNETWORK 2010 Washington DC

List of Figures

Figure 2-1 NGN framework [27]	23
Figure 2-2 HIPT architecture	28
Figure 2-3 NGN RACF within the NGN architecture	30
Figure 3-1 PCE node [26]	37
Figure 3-2 Multiple PCE path computations with Inter-PCE communication [26]	38
Figure 3-3 PCE based MPLS transport network.....	39
Figure 3-4 Per-domain path computation model.....	40
Figure 3-5 BRPC path computation	41
Figure 3-6 BRPC working flow	42
Figure 3-7 Dynamic domain path example	45
Figure 3-8 Inter-domain paths metrics	46
Figure 3-9 DPV updating	48
Figure 3-10 OPNET model	50
Figure 3-11 Connection blocking probability (12 domains).....	51
Figure 3-12 Connection blocking probability (25 domains).....	51
Figure 3-13 Connection blocking probability (45 domains).....	51
Figure 4-1 algorithm of DDP	58
Figure 4-2 MK-DDP algorithm.....	60
Figure 4-3 A*-Dominated algorithm.....	64
Figure 5-1 Carrier Ethernet transport network architecture based on NGN architecture	69
Figure 5-3 Carrier Ethernet with control plane based on NGN	72

Figure 5-4 T-MPLS double label scheme	1
Figure 5-5 Test bed implementation	75
Figure 5-6 SIP client user interface.....	77
Figure 5-7 Resource reservation and commit procedure	78
Figure 5-8 Carrier Ethernet QoS and LSP mapping procedure	79
Figure 5-9. OPNET model for Carrier Ethernet with control plane...	80
Figure 5-10 Traffic classified performance and throughput	84
Figure 5-11 PBB-TE working and backup path.....	85
Figure 5-12 OAM interface.....	86
Figure 5-13 MDI for 1 second update interval.....	87
Figure 5-14 MDI for 100 msec update interval.....	87
Figure 5-15 MDI for 10 msec update interval.....	88
Figure 5-16 MDI for 3 msec update interval.....	88

List of Tables

Table 3-1 Simulation parameters of the network configuration and requests..... 50

Table 5-1Test bed facility 75

Table 5-2 service class provision 83

Table 5-3 LSP bandwidth profile 83

Table 5-4 Subjective evaluation 86

Table of Contents

Abstract	1
Resume	3
Acknowledgements.....	5
Ph.D Publications	7
List of Figures	9
List of Tables.....	11
Table of Contents	13
Chapter 1 Introduction.....	17
1 Background and motivation	17
2 Research contribution.....	18
3 Outline of dissertation	19
Chapter 2 Background and inter-domain routing issues	21
1 Overview	21
2 Next Generation Network	22
2.1 Concept.....	22
2.2 Reference model.....	23
3 Carrier grade transport services.....	24
3.1 Transport technologies	Error! Bookmark not defined.
3.2 QoS Routing	26
3.3 Challenges in inter-domain routing	27

4 HIPT project.....	28
Chapter 3 Inter-domain Routing	33
1 Introduction	33
2 Related Work.....	34
3 PCE based inter-domain routing architecture	36
3.1 Introduction to Path Computation Element.....	36
3.2 PCE based inter-domain routing reference model	38
3.3 Applicability to traffic engineering in MPLS transport network.....	39
4 PCE based Routing mechanism	40
4.1 PCE based multi-domain routing procedure	40
4.2 New approaches towards PCE based inter-domain routing .	43
4.3 Domain Path Vector	44
4.4 DPV updating mechanism.....	47
5 Simulation and analysis.....	49
6 Conclusion.....	52
Chapter 4 Inter-domain routing algorithms.....	53
1 Introduction	53
2 Related work	54
3 Problem statement	54
4 Algorithms.....	56
4.1 Link Weight in Domain Path Vector.....	56
4.2 DDP algorithm	57
4.3 MK-DDP algorithm (with dynamic link length, multiple constraints)	59
4.4 A*-Dominated algorithm	62
Chapter 5 Next Generation Network control plane and testbed .	67
1 Introduction	67
2 Architecture Design.....	68
3 Control Plane Architecture for MPLS TE.....	70
3.1 Requirements.....	70
4 Functional architecture design	71
5 QoS class mapping and policing	73
6 Carrier Ethernet Test bed implementation	74
6.1 Test bed facilities	75

6.2 Functional components	75
6.3 Working procedures	77
7 Result Analysis.....	79
7.1 Control plane simulation	79
7.2 Test bed	82
Chapter 6 Conclusion.....	91
1 Summary	91
2 Future Research.....	92
Bibliography	95

Chapter 1 Introduction

1 Background and motivation

The concept of Next Generation Network (NGN) is leading the future working strength of the future network development. The two reformative characteristics, which are the separation of control and transport functions and the global mobility, accelerate the deployment of network service integrity, traffic engineering, Quality of Service (QoS) and network reliability. On the other hand, high performance transport network with traffic engineering is more and more desirable since the digital traffic explosion and increasing demand for the new multimedia services. With response to these demands, the goal of NGN is to provide a superior framework and architecture that ensure all elements required for interoperability and network capabilities support applications globally.

Another fact stemming in the transport network is that QoS services are described with more complex constraints required by customers. It is desired to develop further transport technologies and control planes that are able to convey the traffic with different forwarding classes and ensured end-to-end QoS. Multi Protocol Label Switch (MPLS) as a label switching protocol naturally support data traffic transporting with finer QoS granularities and more forwarding classes. In the NGN context, MPLS can be seen as a suitable candidate transport function that lying in the transport layer. Nevertheless, it is still a challenge to

design an accompanied routing and control plane as a media that connecting the underlying transport network and service control functions in the mean time make the context fit into NGN.

2 Research contribution

As there are a number of activities are related to the realization of NGN and high performance transport network, we focus this PhD research on providing a high performance MPLS based transport network by means of applying enhanced routing mechanisms and algorithms. Moreover, the functions such as transport network resource admission and control are also applied into this MPLS network in order to realize the carrier class transport services.

This PhD work contributes to the inter-domain routing and resource admission control in the following three aspects:

1. Path Computation Element (PCE) based routing architecture [69] is enhanced with a dynamic domain path computing mechanism. The proposed PCE routing architecture has accompanied with quite a few Traffic Engineering (TE) supported Label Switch Path (LSP) mechanisms e.g. per-domain routing and Backward Recursive Path Computation [70]. Our work specifies a dynamic domain path computation mechanism, which fills the blank of determination for domain path as stated in the RFC 5441.
2. An innovative Domain Path Vector (DPV) is proposed. It is the carrier for the inter-domain link information. It enables the computation of dynamic domain paths that the BRPC mechanism can executes on.
3. Three algorithms are proposed to compute the optimal domain level routing path dynamically. It addresses the issues in multiple constrains routing in inter-domain scale.
4. A resource admission and control plane is applied for MPLS TP transport network. This generic control plane together with a double label LSP provisioning scheme for MPLS supports the flow based traffic forwarding in MPLS TP networks.

3 Outline of dissertation

This dissertation is structured in the following chapters:

Chapter 2 gives the background knowledge about NGN and Carrier Ethernet. It describes concept and architecture of NGN and carrier grade transport service. Several candidate transport technologies and routing protocols are briefly introduced. At last, it lists several issues from the current inter-domain QoS routing network architecture and protocols.

The part of a PCE based inter-domain routing architecture enhanced with DPV based routing protocol is proposed in Chapter 3. In this chapter, we first describe the PCE based routing architecture, and carry out our enhanced routing mechanism with DPV. A routing information updating protocol is also proposed, aiming at reduce the chance in inter-domain path fluctuation. A network model is simulated and the results are presented and analysed as the last part of this chapter.

Chapter 4 focuses on describing the algorithms that computing the inter-domain paths with multiple constrains. In this chapter, we establish mathematic model for the inter-domain network and give necessary definitions. Based on the mathematic model, there are three algorithms carried out. First one is an enhanced link-state algorithm, while the second provides with more than one domain paths. The third one is proposed under heuristic algorithms. The algorithm complexity is listed and simulation is performed.

Chapter 5 is introduces a NGN based control plane for resource admission and control. In this chapter, we apply this control plane into MPLS transport network together with a proposed double label scheme for traffic engineering. The simulation results depict the influence of the resource admission control to the performance of the traffic.

Last chapter concludes the research contributions and introduce several future research possibilities.

Chapter 2 Background and inter-domain routing issues

1 Overview

The market realities reveal great competition among operators due to the reasons such as: deregulation of markets, explosive usage of Internet and increasing demand for multimedia real-time services. Thus, network service providers are deploying value-added services, in order to obtain a larger Average Revenue per Unit (ARPU). Moreover, the needs to transform Time Division Multiplex (TDM) grid into packet-switch based network is seen as the trend in the struggle of providing high performance, carrier grade transport network services.

The ubiquitous presence of networks today has led to an increasing demand of inter-operability and mobility, which cannot be addressed by current network infrastructure. Thus ITU-T carries out the NGN release, where an evolutionary relationship between the network transport and control is defined and Inter-operability and mobility are better supported. Respectively, the emergence of Carrier Ethernet (CE) is promoting the transport network into the era of packet-switching.

This chapter gives introduction of the context of this PhD research in the following sections. Section 2 gives introduction the framework and architecture of NGN, which is the context of this thesis; Section 3 introduces concept of Carrier grade transport services; Section 4 introduces QoS routing protocols and main issues in the current

routing architecture and protocols. The last section made a brief introduction of the HIPT project.

2 Next Generation Network

The Next Generation Network (NGN) carried out by International Telecommunication Union (ITU) is enrolled with features of seamless accessibility and end-to-end quality insurance is now directing both the network operators and service providers' working schedules. The target of NGN is to ensure the interoperability and mobility of all the network elements while maintaining the concept of separation between network transport, service and applications. [27]

From the QoS transport service perspective, the most attractive and valuable proposal in the NGN is the separation of network transport and control functions and a unified, protocol, technology agnostic transport control functions.

2.1 Concept

The recommendation of ITU-T's NGN framework describes the concept and attributes of NGN in these five areas: [27]

- NGN is a **packet-based network** and should be able to provide **any** kinds of telecommunication services.
- It is able to make use of the **multiple broadband and QoS** based transport technologies.
- The service-related functions in NGN **are independent from the underlying** transport-related technologies.
- From the network services providers and users' point of view, it supports **unfettered access**.
- It provides **generalized mobility** which allows consistent and ubiquitous provision of services to users.

2.2 Reference model

The idea of NGN is to keep the diversity of the existing network services and transport technologies while resolve the infrastructure into horizontal and vertical two dimensions on the purpose of declaiming the clear and independent roles on network services and transport functions. Figure 1 shows the logical separation of the services from transport in NGN. The services and transport related functions are located in two independent strata. The benefit of this evolving functionality division is it is capable of providing non-interference services for both the network operators and service providers.

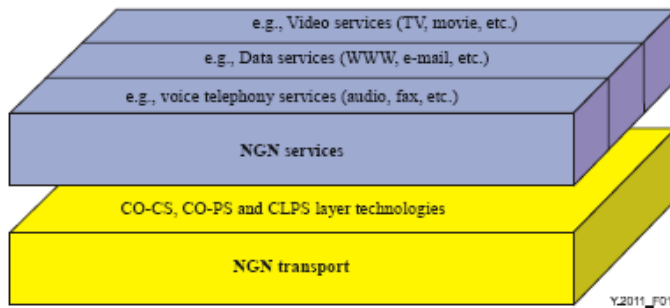


Figure 2-1 NGN framework [27]

The set of transport functions reside in NGN transport stratum provide the connectivity between any two geographically separate points. The point is it is merely concerned with the conveyance of the information and ignoring the contents of the service related data coming from the upper service stratum. There could be several layers (from layer 1 to layer 3) from OSI 7-layer Basic Reference Model (BRM) involved into this plane.

Relatively, there is another set of functions related to the services to be invoked located in this NGN services stratum. It can be all kinds of services such as voice services, data services, video services and multimedia services etc.

From an architectural perspective, the cornerstone is the separation of services and transport functions. For instance, in the NGN service stratum, it is solely concerned with transporting all the service-related data to users in the user plane. In the control and management plane, they provide the functions of the network resource control and management to ensure the availability and quality of the services and applications. The part of NGN transport stratum provides the users with the function that transport data and all the control and management functions related to the transport network resource to carry such data between end users.

3 Carrier grade transport services

As implied by the name, carrier grade transport network means the network is manageable, reliable and capable of high performance transport services. Network providers control the transport services with a finer QoS granularity. Moreover, it also consists of transport with resiliency and security. It is obvious that IP is not a carrier grade technology. A recent development in this area is the introduction of Metro Ethernet in metropolitan and 100 Gb Ethernet. Some service providers are applying Ethernet or MPLS as a carrier grade native packet transport technologies. Two of the typical deployments are Provider Backbone Bridge Traffic Engineering (PBB TE) and Multi Protocol Label Switch Traffic Profile (MPLS-TP).

3.1 MPLS-TP

MPLS is a technology in which data packets are encapsulated at the network ingress routers and forwarded along paths [30]. The paths are called Label Switched Paths (LSP), which are identified by a set of labels. LSPs provide dynamic, transparent virtual network connections with support for traffic engineering. As an intended superior solution for IP based transport services, MPLS is highly scalable and protocol agnostic.

MPLS Transport Profile (MPLS TP) defined by ITU-T recommendations G.8110.1, G.8112, G.8121 is a connection-oriented MPLS based packet transport technology.

The forwarding behaviour of MPLS TP is a subset of MPLS, while abandons the control functions that implemented in the IP/MPLS network. It simplifies the data plane, removes unnecessary forwarding process such as PHP and label merging from the MPLS behaviours, and adds ITU-T transport style protection switching and OAM (Operation, Administration and Maintenance) functions. These simplifications and additions make MPLS-TP a purely transport-oriented and “carrier-based” transport network technology. Moreover, different from the MPLS technology depending control functions, T-MPLS is meant to be independent of the network control plane, which provides wide network scalability and flexibility.

For the goal of traffic engineering and end-to-end transport, MPLS-TP does not support connectionless transfer mode. All the connectivity it provides is explicit. At the beginning, there are several MPLS supported attributes such as LSP merging are excluded by MPLS-TP. However, it turned out to be incompatible with the current MPLS devices and made the network upgrading difficult. So the newly recommendations and RFCs has pointed out that the following attributes in MPLS is optional but not exclusive in MPLS-TE deployment.

- Using bi-directional LSPs (Label Switch Paths).
- No PHP (Penultimate Hop Pop)
- No LSP merging option
- No ECMP (Equal-Cost Multi-Path)

3.2 PBB TE

Combining with features of telecom network, a connection-oriented Ethernet transport solution PBB TE (Provider Backbone Transport Traffic Engineering) emerged in Oct 2005. PBB TE is based on MAC-in-MAC technology defined in the IETF 802.1ah; however, it differs from MAC-in-MAC in some aspects. In 802.1ah, the transport services are connectionless while the path and route of services is pre configured by the network management plane. Since the forwarding table in the PBT supported switches is statistic, the transport services in Carrier Ethernet are actually connection-oriented. Meanwhile, the

telecom transport network requirements of protection, OAM, and QoS are also fulfilled. The existing of the management plane makes the network operator in complete control of resource utilization. In addition, the learning of MAC is disabled to avoid unknown frame flooding. This flooding method will be replaced by unknown frame discarding.

It has been said that PBB TE technologies will be compatible with traditional Ethernet bridge hardware. For the connection-oriented transmission, it could support bandwidth management, Connection Admission Control (CAC) and other Traffic Engineering functions.

4 QoS Routing

4.1 BGP

The Border Gateway Protocol (BGP) is currently the de-facto standard routing protocol in multi-domain routing. It currently release was specified by the Internet Engineering Task Force (IETF) in 1995 [3]. BGP has been proven that it is an efficient and scalable protocol for inter-domain routing, among years of deployment and applied with the Autonomous Systems (AS). However networks that are simply running conventional BGP protocols for inter-domain traffic routing cannot get other routing information other than connectivity. Along with the growing research interest in the area of inter-domain routing, BGP is not sufficient for the most requirements desired by the networks that are willing to provide QoS based transport services. Although there are plenty of ongoing researches that enhance BGP to convey QoS information, the completely distributed routing architecture still has the risk to suffer the issues of network scalability and unavoidable QoS information updating can also lead to an instable network.

4.2 PCE

IETF PCE working group proposes Path Computation Elements (PCE) with the intention of specifying an alternative inter-domain routing

architecture by forwarding routing computation workload to the per domain centralized element. This PCE based routing architecture is not for the internet scale network, it is for the MPLS or GMPLS TE (Traffic Engineering) path computation. The mechanism that centralizes the computation workload per domain somehow upgrades the network stability. The flexible routing architecture and capability of centralized computation convince us to adopt the PCE basic architecture as our research starting point. The intention of PCE based routing architecture is for the computation of TE path for MPLS or GMPLS LSPs. It means the scale of PCE is not for the internet but for a limited number of domains.

4.3 Challenges in inter-domain routing

As been introduced in the above chapter, BGP was intended to route among inter-domain network in a best-effort single path manner. The current release of BGP supplies a slow reacting and limited routing protocol, which is inadequate to handle most of the emerging demands for inter-domain functionalities. The current release of BGP lacks of QoS routing capabilities which has been already recognized as a strong need by the IETF. [2]

Single path: in the consideration of scalability and confidentiality, BGP is designed to provide only one path to each destination entry. Apparently it is not compliance with traffic engineering requirements. Control planes get limited connectivity information to route traffic in a more optimized route distribution when it is possible.

Scalability: In inter-domain network routing, the routing protocol is required to disseminate the routing information in a more scaled manner. BGP provides only connectivity information one entry per destination to cope with the scalability issues which is inadequate for inter-domain traffic engineering.

Quality of Service: although there are plenty of algorithms and protocols that are able to compute the end-to-end QoS assured path under certain constrains in one domain, the issues to compute inter-domain QoS routes are still not well addressed due to many reasons. First the network links and topologies are not transparent to the route

computation algorithms, especially when the computation elements are distributed allocated.

Security: it is not uncommon that network operators need to keep their own network under a certain level of secure. It is with the consideration to be competitive, in the other hand, to prevent the network resource being abused by malicious ways.

5 HIPT project

As a response to the emergence of NGN and the requirements from high demanding services such as HD IPTV, we proposed HIPT project -- High quality IP network for IPTV and VoIP to Danish Advanced Technology Foundation. The objective of the HIPT project is to enhance Carrier Ethernet transport for IPTV applications by developing technologies and network architectures that can fulfil the increasing requirements in terms of bandwidth, reliability, quality and at the same time reduce cost of network operation.

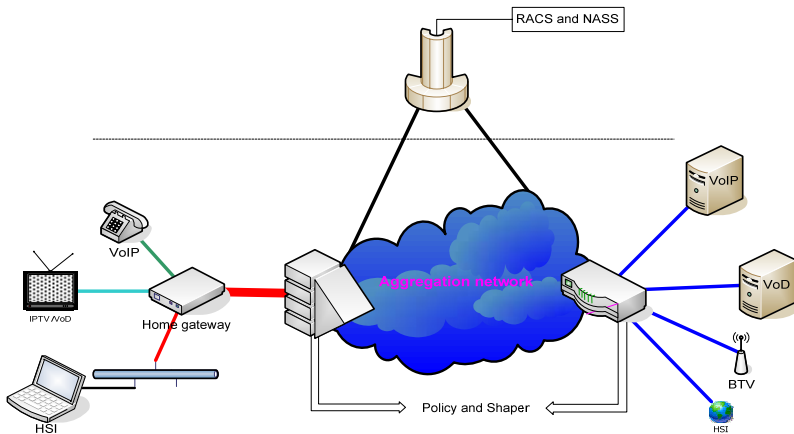


Figure 2-2 HIPT architecture

Figure 2-1 demonstrates the proposed architecture of HIPT project. In this project, we focus on bringing the benefits of the Carrier Ethernet transportation services in the context of NGN architecture. Moreover, the transport control plane from NGN is applied for the services

coordination. As the facts of nowadays network situation, it is more and more diverse and mobile from the access network to the core network and Internet. As shown in figure 2-1, The L2 network part between the IP DSLAM and the Edge router is assumed to be based on either T-MPLS or PBT-TE. In both cases, the objective is to transport IPTV signals with carrier class quality but at the same time reduce cost by utilizing carrier Ethernet technology. There are three challenges that we have faced in HIPT and they are described respectively in the below sections.

Management and control plane based on the NGN architecture

Along with the rapid development of technologies of access and transport networks, the interoperability among different network layers, access technologies and operators is becoming an issue. ITU-T Recommendation Y.2001 has stated in the characteristics of NGN that the decoupling of service provision from transport and provision of open interfaces and the independence of service-related functions from underlying transport technologies. Accordingly, in Recommendation Y.2011 General principles and general reference model for Next Generation Networks, a general NGN functional model is carried out, where the service and transport is decoupled. In ITU-T Rec. Y. 2111, a reference model of Resource and admission control functions (RACF) in NGN is specified. As illustrated in Figure 2-2, the NGN can be divided as below three function blocks with the respects of service and transport separation. The RACF stands in the middle between service plane and underlying transport networks. The interfaces between function blocks are unified on the purpose of the layer and technology interoperation. RACF executes policy-based transport resource control upon the request of Service Control Functions (SCF).

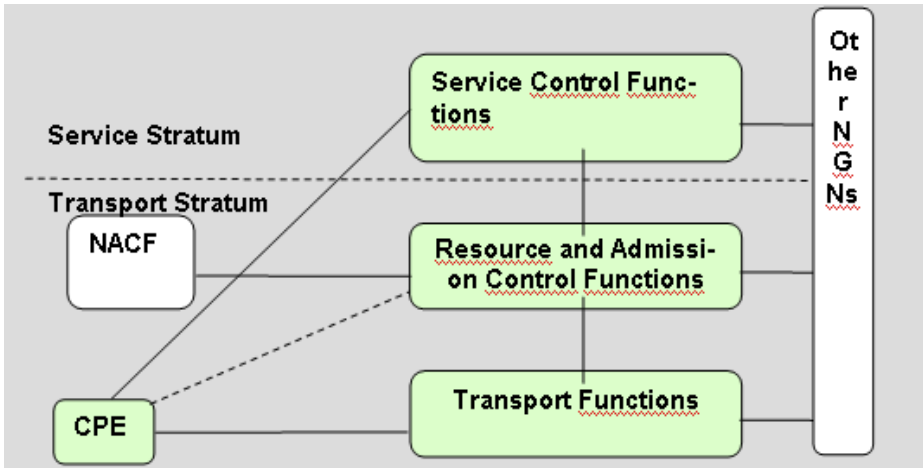


Figure 2-3 NGN RACF within the NGN architecture

In relation to the control plane standardized within NGN, the goal of HIPT project is to apply the RACF reference model into the transport network for resource admission and control. Since RACF is underlying transport technologies agnostic, it is applicable to both MPLS TP and PBB TE networks.

OAM functions for layer 2 flow monitoring

It is desirable for the carrier grade transport network to deliver the required Operation, Administration and Maintenance (OAM) functions. Draft standard IEEE 802.1ag Connectivity Fault Management (CFM) has been recently developed to address the lack of end-to-end OAM in traditional Ethernet networks. In relation to OAM, the goal of HIPT is to be able to find a clear relation between user quality of experience and quantitative measurements in order to determine the threshold for sufficient network layer QoS. The vision is then to enable the Carrier Ethernet infrastructure to detect QoS degradations below the threshold by appropriate OAM mechanisms in the network layer. The level of IPTV awareness in the network layer OAM functions is a topic of research in HIPT.

Fast network resilience and survivability

In PBB-TE, working and protection paths are pre-calculated, and the forwarding tables in nodes on these paths are provisioned/configured with the required forwarding entries. Both the working and protection traffic uses the MAC address of the destination node to fill the Destination MAC Address field. Working traffic uses the VID value assigned for the working path. A different VID value is used to forward the traffic along the protection path. Faults are detected and forwarded using a subset of 802.1ag connectivity fault management. Loss of Continuity Check is interpreted as a fault and also triggers protection switching. During path protection switching, the source nodes swap the VID value to redirect traffic onto the preconfigured protection path. If span or local-bypass protection is used, VID tags are swapped at transit locations that bracket the failed span, node or sub-network connection. Switch-over times are short, because the required VID value and path are preconfigured.

Survivability is specific to the transport network. T-MPLS therefore defines its protection capability using ITU-T's Recommendations G.8131/Y.1382 (T-MPLS linear protection switching with 1+1, 1:1 and 1:N options) and G.8132/Y.1383 (T-MPLS ring protection switching). MPLS Fast ReRoute (FRR) capability requires the use of LSP Merge that is excluded from T-MPLS.

Network survivability traditionally deals with connection recovery after infrastructure or equipment failures, e.g. cable cuts or node outages, which are characterised by loss of signal. In addition to these “hard failures”, users of IPTV may experience signal quality degradation as a “soft failure”, caused by gradual component degrading or malfunction. Since the customers' perception of the signal quality is critical for the success of IP-TV, survivability measures related to “soft failures” will be investigated in HIPT.

Chapter 3 Inter-domain Routing

1 Introduction

When it comes to providing inter-domain MPLS network with traffic engineering LSPs, BGP is not considered as the de-facto routing protocol any more. As we have demonstrated in the last chapter, networks that are simply running conventional BGP protocols can not obtain other information aiming at computing TE LSP than connectivity. BGP protocol is carried out with the intention to exchange the connectivity information in a scaled manner since scalability is an essential requirement for inter-domain routing protocols. It scales the routing behaviors in providing single path with very limited policy based control mechanism. However, MPLS transport network under our concern has a limited number of domains rather than global Internet scale. Accordingly, the establishment of LSP TE may require information such as inter-domain link utilization and QoS parameters (delay, jitter, error rate, etc).

IETF PCE working group proposes Path Computation Elements (PCE) with the intention of specifying an inter-domain routing architecture that supports the LSP TE computing. It introduces PCE with flexible routing control architecture to be adaptable to different MPLS based network scenarios. Moreover, it also specifies a set of signalling and routing information dissemination protocols and mechanisms in correspondent with the architecture. The flexible PCE based

architecture better addresses the inter-domain QoS paths computing. First, inter-domain routing is not constrained with BGP. Secondly, the workload of LSP TE path computation is forwarded to PCE. The mechanism that centralizes the computation workload per domain somehow upgrades the network stability. Moreover, in order to achieve optimal QoS path computation of within a group of domains, the PCE working group carries out BRPC (Backward Recursive Path Computation) [2] mechanism. By means of BRPC mechanism, it is possible to compute TE based inter-domain path, in the meantime, keep the domain independency and confidentiality.

In general, network routing consists of two basic tasks [23]: distributing the network information and searching for the best feasible paths. Hence, this project firstly focuses on carrying out efficient and scalable network information exchanging mechanism.

In the following sections, we will first introduce the PCE based inter-domain routing architecture, followed with an innovative Domain Vector based, domain-link-state routing protocol. In the last section, a simulation model will be introduced and several simulation results will be analyzed.

2 Related Work

There are plenty of ongoing researches on achieving the QoS routing and LSP establishment in MPLS based inter-domain network. From the argument of routing architecture and protocol, the researches can be categorized into two classes, one focus on extending the BGP protocol with carrying TE information, the other is attempting to design a new architecture or protocol beyond BGP as PCE.

A. Manolova et al proposed BGP with TE extensions for GMPLS inter-domain routing [8]. T. Zhang et al extends BGP protocols with a QoS extension, which can compute the multiple constrained QoS paths [10]. M. Yannuzzi et al carried out a distributed overlay entities for inter-domain QoS routing. The proposed overlay entity (OE) tuning its static QoS provisioning using either QoS aware BGP (QBGP) or TE-BGP. The bottom layer consists of QBGP routers,

which is able to distribute QoS information and take routing decision per Class of Service (CoS). X. Masip-Bruin et al in [33] described their project EuQoS, which aimed at building an entire QoS framework, addressing all the relevant network layers, protocols and technologies. In this project, it proposed EQ-BGP. EQ-BGP extends the BGP-4 in several ways. It conveys QoS information with QoS-NLRI and assembles QoS information for computing the aggregated values for the entire routing paths. Additionally, it extends multiple routing tables in order to store the available paths for different end-to-end services. R. Prior et al define an extension to the BGP routing protocol QoS_INFO. QoS_INFO gathers routing QoS information along the candidate routes and update the information according to the QoS attributes (additive, manipulative, concave, etc). In this way, more than one QoS constraints can be concerned during the route selection process.

Other than extend BGP protocol to carry QoS information, there are quite a few researches that propose alternative approaches trying to go around enhancing the existing BGP. PCE is one of the most considered elements that can be introduced in enhancing the capability of QoS path routing and computation. M. Chamania et al proposed an adaptive PCE framework to improve the inter-domain traffic engineering and resource utilization [19]. It keeps the transport performance in the high level by pre-reserving resources for inter-domain transit traffic. Besides, a scalable inter-domain advertisement mechanism is also proposed here. The idea the QoS parameters are only advertised when the values are out of the specified bounds. As long as the values or combined values are kept within the bounds, it is not going to send the update information to other domains. Another project [35] locates the service plane over PCE to provide automatic inter-domain connection-oriented services. It builds service plane for inter-AS GMPLS-TE and take the advantages of the PCEP, Traffic Engineering Database (TED) and Backward Recursive Path Computation (BRPC) mechanisms that are carried out accompanied by the emergence of PCE architectures. As mentioned by many research, in the scope of PCE based inter-domain routing, BRPC is proved to be one of the best mechanism achieving establishing end-to-end QoS path. R. Casellas et al in [36] adopt the PCE base inter-domain routing architecture in GMPLS while enhanced BRPC mechanism with the capability to meet the Wavelength Continuity Constraint (WCC). G. Geleji et al compares the different PCE based

inter-domain routing schemes [32], the work verifies that BRPC approach improves the inter-domain routing capability. D. Zhu et al in [9] carries out a feedback based routing by proposing a probing feedback mechanism.

3 PCE based inter-domain routing architecture

As introduced in *Chapter 3*, the ITU-T has made a great effort in standardizing the NGN Release 1. We decide to design this inter-domain routing architecture compliance with the NGN context. Since the objective routing area is not intended to be Internet, here we use PCE based inter-domain routing architecture (Figure 2) as the basic reference model applied in this routing architecture.

3.1 Introduction to Path Computation Element

Path Computation Element (PCE) is an entity that is capable of computing a network path or route based on a network graph [26]. Differ from BGP routing entity that provide a single routing entrance according to certain policies, PCE is be able to apply computational constraints during the route computation and provide more than one path candidates. PCE is applicable in both intra- and inter-domain routing area to finding the routes according to the requested constrained.

Figure 3-1 presents PCE node architecture with two (or three) function entities. A PCE node can be seen consist of three function components or entities: TED, PCE and Signaling Engine. TED stands for Traffic Engineering Database. TED contains the topology and network resource information. The information obtained by TED is used for assisting PCE computing the constraint traffic engineering paths. The path computation requests are received by component PCE. The PCE returns with the paths that are computed according to the routing requests. It communicates with other PCEs in the adjacent nodes if necessary. Signaling Engine is the entity where all the routing protocol related signaling takes place.

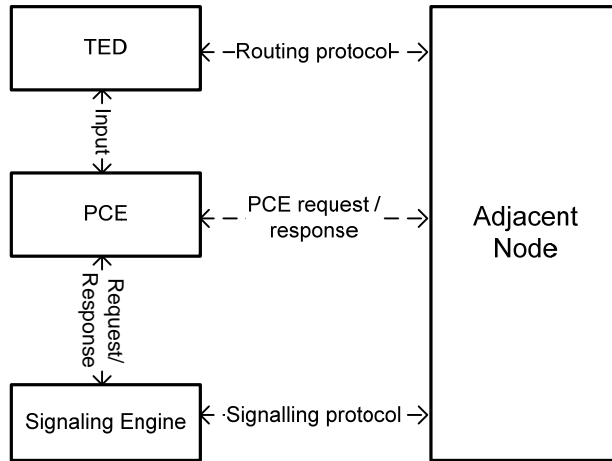


Figure 3-1 PCE node [26]

The routing protocol is used to exchange and update the routing information between PCE and its adjacent nodes, in such way, TED can provide PCE with the updated information when it requires. Signalling engine

Note that this PCE node composition figure shows the relations of the functions entities within PCEs and between PCEs and adjacent nodes. It does not confront PCE or any entities with any specific placement. In the other words, Figure 1 is the logical relationship among TED, PCE and signalling engines. Their physical entities are not necessarily placed together within one device. According to the requirements, sometimes the signalling engines are bounded together with the edge routers while the other two are placed in another separated device.

Since the objective of this project is to carry out QoS constraints inter-domain routing architectures, we focus on PCE based inter-domain routing architecture in the next section and give our own inter-domain routing architecture.

3.2 PCE based inter-domain routing reference model

Since we have stated in the beginning of this chapter, the PCE based architecture is applicable to MPLS/GMPLS networks that require the establishment of TE LSPs within single domain or a number of domains. It is worth to mention that this architecture is not possible and not desirable to be applied to the global internet scale.

The reference model we design for inter-domain routing based on PCE is depicted in Figure 3-2. We are coping with the issues within inter-domain routing. Thus, we decide to have one PCE residing in one domain, which can in charging of both the intra- and inter-domain QoS path computation. PCEs exchange path computation request / response by means of Path Computation Element Communication Protocol (PCEP).

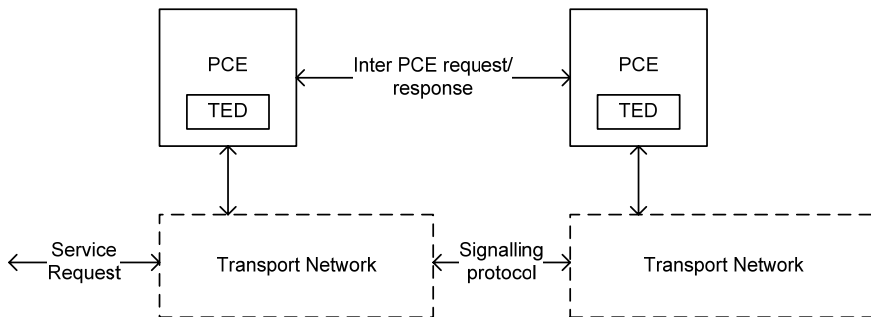


Figure 3-2 Multiple PCE path computations with Inter-PCE communication

3.3 Applicability to traffic engineering in MPLS transport network

To establish traffic engineered LSP in inter-domain network, we proposed the network routing architecture with control and route computation functions as shown in Figure 3. In this architecture, PCEs in every domain (AS) consist the routing control plane. They communicate with each other through the signalling engine as described in the above section. In the NGN context, PCEs can be seen as cooperating with the transport control plane RACF. The latter one is in charge of the resource admission control in the mean time, providing PCEs with necessary intra-/ inter-domain resource information. Routers or Area Border Routers (ABR) send routing requests to the PCE. PCEs compute and responses back with resulting paths.

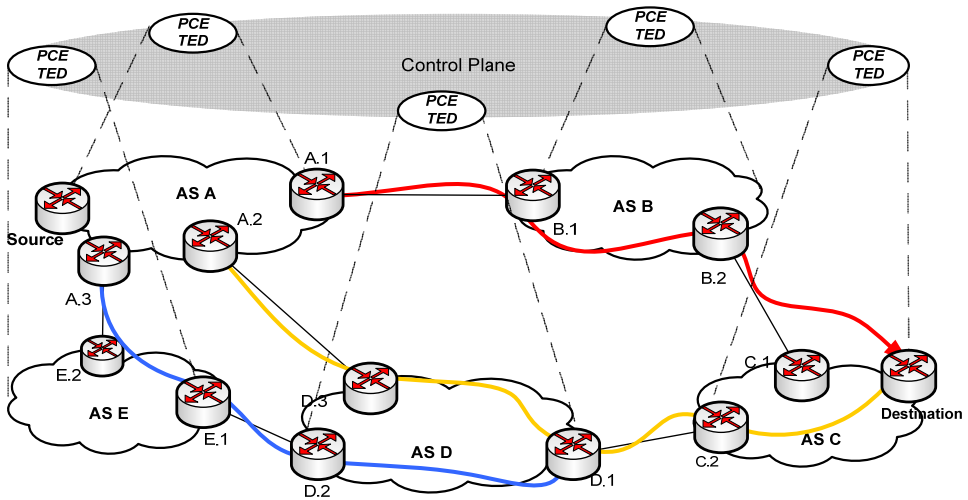


Figure 3-3 PCE based MPLS transport network

4 PCE based Routing mechanism

4.1 PCE based multi-domain routing procedure

4.1.1 Per-domain routing

The scenario of PCE based per-domain routing is derived from RFC 5152, which describes a per-domain path computation model for establishing. In general cases, networks that are running per-domain path computation protocol have limited visibility to the conditions of other networks. The ABRs of each network are typically BGP peers, and runs IGP protocols within each domain. ABRs compute inter-domain paths segment within the iBGP routing areas. Finally all the paths segments are stitched into the complete inter-domain path. This model can be applied to PCE based inter-domain routing architecture. As shown in Figure 4, in this case, PCE residing in each domain or AS compute the TE LSP within its own domain. The TE LSP within each domain is then forwarded to the next hop along the path that computed by a certain method such as BGP. In this way, each sub LSP is computed under the TE constraints. However, the stitched complete LSP cannot promise to be optimized as described in the general case.

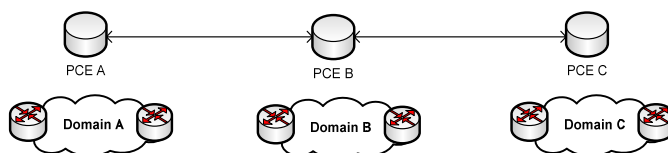


Figure 3-4 Per-domain path computation model

The main problem prohibiting the per-domain path computing obtaining the optimized TE LSP is the invisibility among domains and lack of cooperation between PCEs.

4.1.2 BRPC routing procedure

BRPC procedure establishes end-to-end QoS paths by obtaining Visual Shortest Path Tree (VSPT) in a recursive way. As show in Figure 3-5,

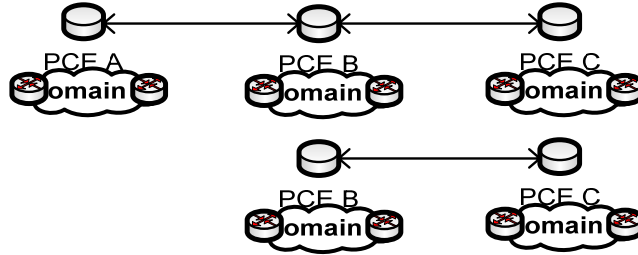


Figure 3-5 BRPC path computation

Backward-Recursive PCE (Path Computation Element)-based Computation (BRPC) procedure provides the PCE with the ability of computing shortest constrained inter-domain paths without disseminating operational topology information to other domains.

In our project, BRPC procedure is considered as one of the most efficient and applicable mechanism for establishing shortest constrained LSPs. Hence we introduce the basic working flow (Fig. 2) of BRPC in order to make our further proposal based on this procedure more understandable.

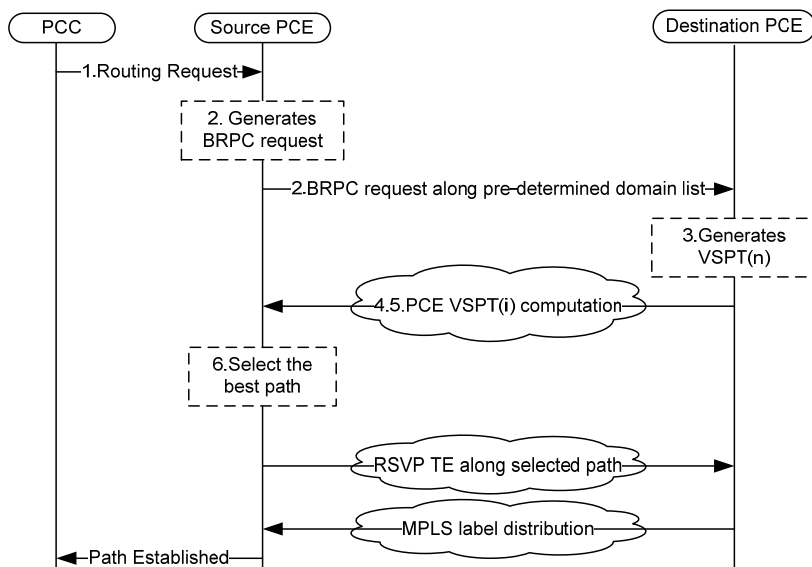


Figure 3-6 BRPC working flow

1. PCCs send routing requests to their own domains PCE. If there are more than one PCEs residing in one domain, a PCE discover protocol will be called to choose the most suitable one.

2. The source PCE sends BRPC request and forwards it between PCEs until reach of the destination domain. BRPC requests traverse along the domain path that pre-determined offline or by administration means.

3. PCE in the destination domain creates a tree of shortest constrained paths within its own domain—VSPT (Visual Shortest Path Tree). Destination PCE computes VSPT(n), the tree made of the list of shortest constrained paths between every previous PCE and the TE LSP destination.

4. This VSPT will be passed to the previous PCE that sends request.

5. PCEs along the domain list receive the VSPT in the order that decided in advance. PCEs get the BRPC request and compute the VSPT(i) by inquiring the TE information from TED, i.e. PCEs along

the domain path extend the VSPT(n) with the computed inter-domain path and pass the extended version to the next domain.

Eventually, VSPT contains the shortest constrained paths for every domain along the routing paths passes back to the source PCE. Thus source PCE is able to compute the optimal LSPs after analyzing the TE information collected by VSPT.

To describe this procedure more visualized, we take the example of the network architecture shown by Fig. 3-3. Source PCC in AS A makes a request to its domain PCE. The BRPC request is forwarded until reaching the PCE in the destination domain AS C. After receiving this BRPC computing request, PCE in domain C creates and initializes VSPT between source and destination domains. The pre-determined domain paths show that to route from AS A to AS C, the LSP can be established among domain paths (A,B,C) (A,E,D,C) or (A,D,C). From domain C, it sees domain B and D as the downstream domains. So it computes the shortest constrained path between ingress router C.1 and C.2 to destination PCC. These two paths are added into this VSPT as its VSPT(n) (Destination-router to C.1, Destination-router to C.2). The VSPT message is then forwarded to both domain B and D and the same procedure is executed until reach the source PCE.

4.2 New approaches towards PCE based inter-domain routing

One of the assumptions declared in the RFC is the domain sequences that the BRPC procedure computes the optimal paths with are pre-determined. In another words, each time for the request with the same source and destination address, the TE LSP will be computed among the same set of domain paths. It is not difficult to imagine, when the number of transit domains is under a limited amount, i.e. the domain hops between any source and destinations are limited, the optimal paths computed among several fixed domain paths will not vary a lot from the paths that are computed among dynamic domain paths. However, for the inter-domain network scenario containing larger number of domains, running BRPC procedure among fixed domain paths limits the TE computation and can also degrades the optimization of the whole network resource utilization. On the other

side, the dynamic domain path computation method can handle the traffic burst better than the fix domain scenario, i.e. when the traffic from one direction give a heavy load compare to the other directions, a dynamic computed domain path can switch the traffic to other light load domain path and reduce the burden on the original path.

The task of obtaining a set of dynamic domain sequences that can be followed by PCEs when running BRPC procedures can be investigated by several aspects. It can be considered as designing a routing protocol, that exchange the domain level routing information while fulfill the additional requirements for TE inter-domain routing. Moreover, the task can also be regarded as looking for some algorithms that are able to compute the domain level routes, which support TE and optimize the network resource. In the following sections in this chapter, we are going to propose an inter-domain information exchanging protocol that enables the TE routing information exchanged between PCEs while take the overhead and confidentiality into consideration. It follows the similar link-state-like protocols procedure while the disseminated TE information represents the TE information of domain-level routes instead of link-level within a single domain. The innovative algorithms that compute optimized domain-level routes will be presented in the next chapter.

In the rest of the sections, Domain Path Vector (DPV) will be introduced first. It carries the domain-level routing information and can be disseminated to other PCEs. Secondly, to avoid the routing route fluctuation, a DPV updating procedure is proposed here. Finally, the DPV based inter-domain routing scenario is simulated by OPNET together with other scenarios such as fixed domain BRPC procedure. The simulation network collects the results of overhead and network resource (network link) utilization.

4.3 Domain Path Vector

To cope with the issue that the BRPC procedure computes the paths across a pre-determined domain sequence, we propose a domain route update mechanism inspired by the previous research [4][6]

In the case of pre-determined domain path, TED within PCEs keeps record of the resource usage of its own domain and provides connectivity and resource availability information to route computation entities of its own PCE. To enable the PCE compute the route across dynamic domain path, we enhance TED with the metric shown in Fig. 3. The index of the two dimensions are the AS number of neighbor domains. The value of the metric element is the weight of the shortest constrained inter-domain path between these two neighbor domains. For example in Fig. 1, domain D has three neighbor domains: A, E and C. so the size of its metric will be 3x3. W12 is the weight of the shortest constrained path that domain D can provide for the data traffic to traverse between domain A and E.

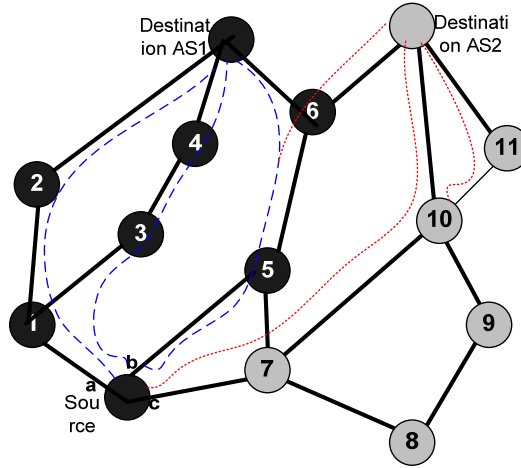


Figure 3-7 Dynamic domain path example

For the description of following proposal, here we bring two definitions to describe the inter-domain network topology.

Definition 1: Domain Link (DL). Let i be the neighbor domain of domain v , Domain Link $l \{v, i\}$ denotes the directly connected link between domain v and i .

Definition 2: Domain Connecting Link (DCL). Let i, j be two different neighbors of domain v , the DCL $l \{v, i, j\}$ denotes the best path domain v can provide for transporting the incoming traffic from i to j .

Here DCL is not necessarily to be the directly connected links between domains.

	D1	D2	D3	D4	...	Di
D1	W11	W12	W13	W14	...	W1i
D2	W21	W22	W23	W24	...	W2i
...
Dj	Wj1	Wj2	Wj3	Wj4	...	Wji
...
Di	Wi1	Wi2	Wi3	Wi4	...	Wii

Figure 3-8 Inter-domain paths metrics

Every time when there is path commitment or teardown within a domain, TED will keep record and update this metric as well, for our first research stage, the path weights are only related to the available bandwidth. Whenever the weight element in this metric drop down to a threshold value (i.e. less than 15 % of the maximum link bandwidth) this element is disseminated to the TEDs in other PCEs. Upon receiving the updated information, TEDs re-compute their domain path according to a preferable algorithm (In our project we use Dijkstra). Path weight Updating procedure is also trigger whenever the path weight goes back to the normal range.

It is worth to notice that the dissemination of this metric or the element is scalable as long as the cooperative domains are under a certain limited number (i.e 50 domains), because the bandwidth information is disseminated by a threshold triggered mode rather than disseminated every time the path weight get changed. Another point is that this concept of path weight metric is not against the confidentiality among domains since there is no detailed operational topology information, other than the total available bandwidth value for the paths between two neighbor domains.

4.4 DPV updating mechanism

Owing to the different requirements, routing information dissemination for inter-domain plays an important role in the routing performance. First, the inter-domain routing information cannot be disseminated in the same manner due to the scalability issue. Second the routing decisions and policies are different from different network operators. Thus the content of the routing information have to convey not only connectivity information, but also information such as traffic engineering, QoS and other policies coming from different operators. The last requirement has been addressed by the DPV in the way that domain path vectors convey information without showing the topology details. The knowledge such as traffic engineering or QoS can be obtained from domain path vectors after negotiation between operators. The first scalability requirement has been one of the issues that are always taken into consideration for inter-domain protocol design. There is trade off between the routing message overhead and routing accuracy. However there is another balance that has to be noted, such as between the routing accuracy and the routes fluctuation. The mechanism in figure 3-9 shows way to take into the consideration of routing stabilities and the accuracy.

The DPV updating mechanism has effect on two aspects: to reduce the routing overhead and to precaution the potential overloaded link. The idea of this DPV updating mechanism is that the information will not be disseminated before there are strong evidence illustrate that there is need to update the inter-domain routing paths. In our computation scheme, there is no statistics prediction for the trend of the incoming traffic. A statistics prediction is normally dealing with the networks that carry regular traffic pattern. For the networks such the traffic pattern such as bursty, it requires a mechanism that can avoid the paths fluctuation. In our project, we introduce a trade off updating mechanism that take both routing paths stability and accuracy into account. First we introduce the low and high weight observing bound for the DCL and DL $\langle L1, L2 \rangle$, $\langle H1, H2 \rangle$. The idea is: when the weight of DCL or DL is outside the bounds, the PCEs do not disseminate the updating information to other PCEs. As soon as the weights go below or beyond the bound, the PCEs send the updating message immediately. When the weights drop into the bounds $\langle L1$,

L2>, <H1, H2>, the PCE updating mechanism switches into “observing state”.

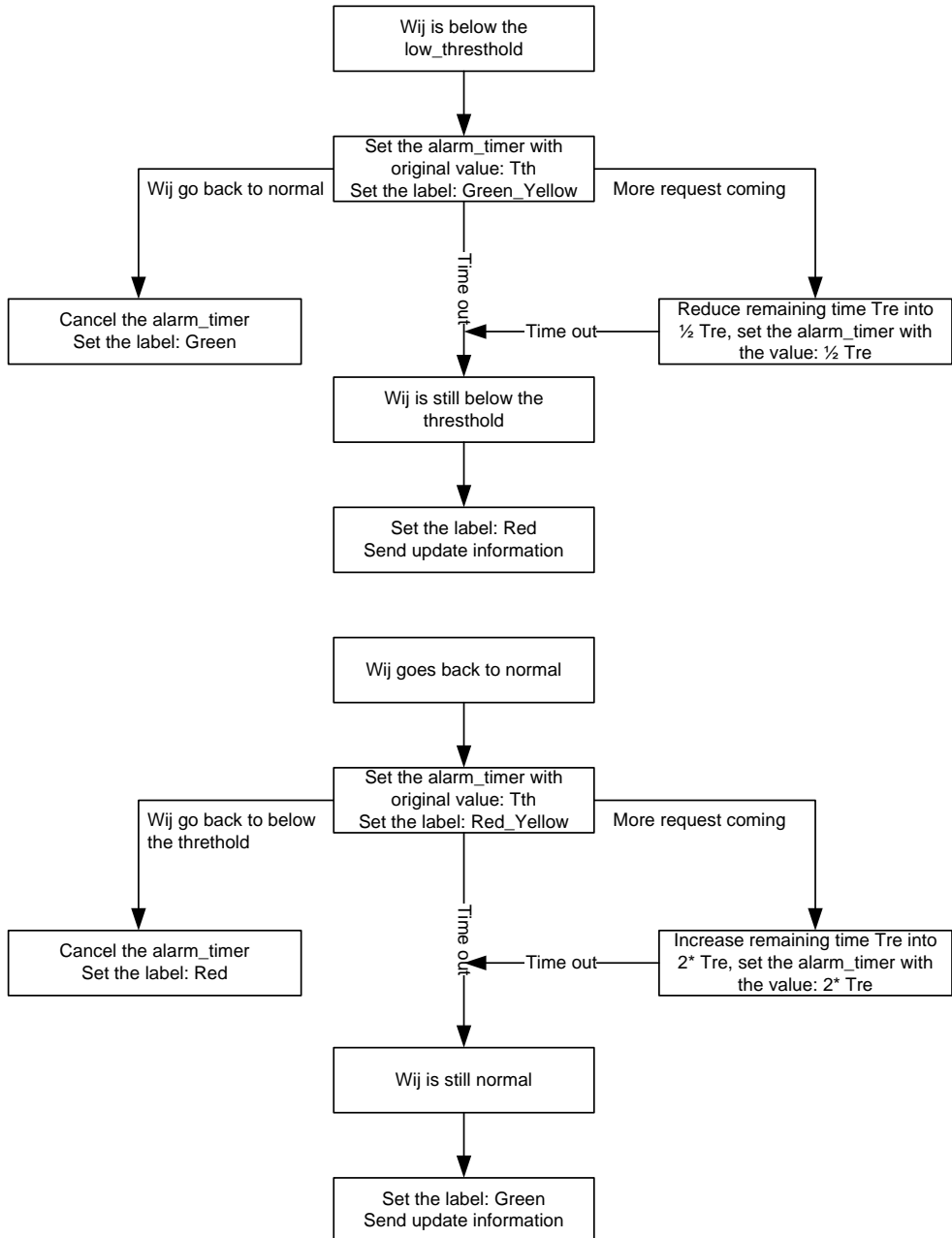


Figure 3-9 DPV updating

5 Simulation and analysis

To verify and demonstrate the performance improvement of our dynamic domain path proposal, we implement an OPNET model of PCE based inter-domain routing network.

Fig. 4 shows the network topology of the scenario that contains 12 AS domains. Each yellow cloud represents a domain and has one correspondent PCE to compute the inter-domain paths for it. Since the goal of this OPNET model is to research on the performance influence that the updates of domain path bring, we make several assumptions for our OPNET model: first, the signaling protocol among PCEs and between PCE and PCCs are implemented as remote process interrupts, since we are not researching on the signaling overhead during this stage; second the data plane of this model is not implemented, the analysis of traffic transfer behavior after the connection establishment is also not the current goal; third, as we mentioned in the description of Computation of Dynamic Domain Path (Section 3), we measure path weight with the available bandwidth and send the updated information when the available bandwidth drops down to a threshold or goes back. Only border routers (PCCs) that are in charge of inter-domain routing are simulated, and the intra-domain paths are not considered. The inter-domain paths can be seen as aggregated paths between border routers.

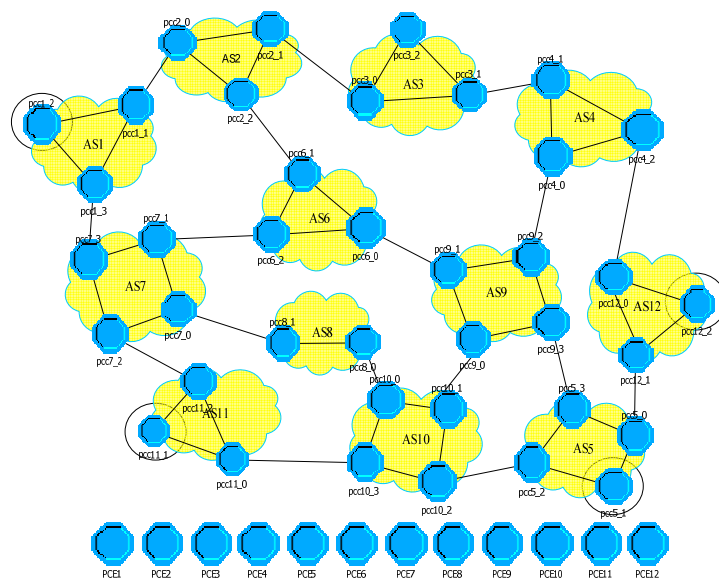


Figure 3-10 OPNET model

$$CBP = \frac{NumberofrejectedConnections}{NumberofTotalConnectionrequests} \quad (1)$$

Table 1 lists the parameters of this simulated network configuration and the routing requests and the traffic load is calculated as Erlang formulation.

Table 3-1 Simulation parameters of the network configuration and requests

Intra-domain link	20 Mb
Inter-domain Link	100 Mb
Reserved path bandwidth	1 – 5 Mb

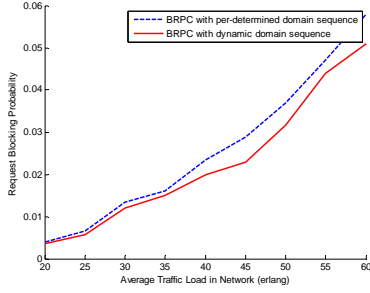


Figure 3-11 Connection blocking probability (12 domains)

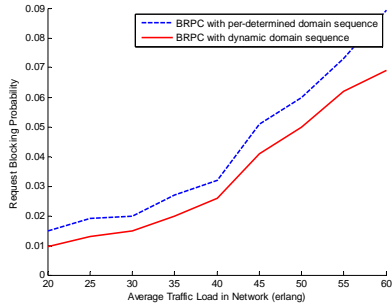


Figure 3-12 Connection blocking probability (25 domains)

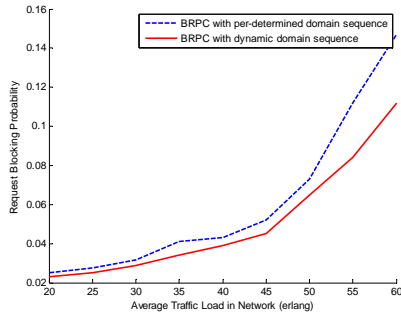


Figure 3-13 Connection blocking probability (45 domains)

As shown in Figure 3-11, the difference of the blocking probabilities between these two BRPC procedures is limited. The reason is described when the BRPC procedure is introduced in the above sections. For the inter-domain network with a limited number of domains, the options of domain paths are also limited, in another word, although the PCE has the ability to compute the domain path dynamically, there is not so much space for the PCEs to switch the inter-domain traffic to. For the network with a larger scale (Figure 3-

12), there is a larger chance to switch the congested traffic by means of the dynamically computed domain paths.

However in Figure 3-13, it is noticed that although the enhanced BRPC procedure shows the advantage in the blocking probabilities improvement, the absolute number of connection blocking probability increases faster compares to the network with 30 domains. This phenomenon reflects the influence of the metrics that the PCEs rely on to compute the dynamic domain paths. In this simulation, the available bandwidth is the only parameter that affects the weights of inter-domain paths. The domain paths are updated simply upon to the changes of the maximum available bandwidth along the paths. Rejecting the connection request only by referring to the available bandwidth information leads to a larger rejection rates. Thus we can get the conclusion: without a well designed inter-domain path metric, the blocking probabilities grow no matter which BRPC procedure is applied, when the network scale is larger than a certain limit.

6 Conclusion

BRPC based inter-domain path computation procedure is an outstanding routing mechanism for computing the inter-domain TE LSPs. However the shortcoming brought by the fixed domain paths is obvious and not avoidable. The enhanced BRPC procedure inherits the same routing protocol of computing the optimal inter-domain TE path but over more dynamic domain paths. The BRPC routing procedure over dynamic domain paths improves the TE performance by the observation of the connection blocking probability.

The simulation results also show a great space in improving this enhanced BRPC procedure with a better designed metric to reflect the traffic pattern on the dimension of domain scale. To make our enhanced BRPC proposal more scalable is the goal of our next simulation in the foreseeable research work.

Chapter 4 Inter-domain routing algorithms

1 Introduction

PCE based inter-domain routing architecture brings capability to compute inter-domain routing shortest constrained TE paths. It provides a flexible network context to disseminate the QoS information and computing the shortest path. In the previous chapter, we carry out the domain-based routing mechanism benefits by the PCE based architecture and a set of signaling and routing protocols.

However, an optimized traffic engineering and utilization cannot be promised by merely enhancing the routing architecture and protocol. Good algorithms are desirable for paths computing within PCEs.

The algorithms to compute the paths executed by PCE also play an important role in achieving end-to-end QoS while improving the network utility TE. Based on the DPV routing protocol carried out by last chapter, here we focus on searching for best feasible inter-domain paths with the respect to given QoS constraints. The goal of QoS routing is to find paths that satisfies multiple QoS constraints while achieving overall network resource efficiency [37]. The problem in QoS routing can be summarized.

According to the type of solutions, QoS path computation algorithms can be exact, approximate or heuristics. According to the routing

scope, the algorithms also have to take the distinct requirements between inter-domain and intra-domain into consideration.

2 Related work

Previous relevant works on algorithms of MCP or MCOP has been achieved through various break points.

[39], [40] deal with the multiple objective computation in a statistic way. In [39], Hichem Ayed et al assume that the delay value for a given link has an unknown distribution. The values of delay and jitter are obtained approximately based on empirical mean and variance. Li Xiao in [40] brings in two new QoS metrics for bandwidth and delay, which the values are based on the statistic prediction. It is aiming at increasing the scalability for the proposed extended BGP protocol. The statistic approaches assume the QoS parameters can be predicted.

Another approach to solve the MCP or MCOP problem is based on heuristic computation. The work described in paper [42] carried out an admissible searching algorithm A*. Different from the above mathematical algorithms, A* algorithm combines the mathematical and heuristic approaches to reduce the “look ahead” effort in searching paths. It is also promised to be able to find the minimum cost solution paths.

3 Problem statement

In this section, we will introduce the notations and definition needed to formulate the MCP protocol into mathematic model.

Definition 3: Domain Path (DP). For a source and destination pair $\{s, d\}$, $p \{s, d\}$ is formed by a sequence of alternative adjacent Domain Link and Domain Connecting Link:

$$p\{s, d\} \leftarrow l\{s, i\} + l\{i, s, j\} + \dots + l\{n, m, d\} + l\{m, d\}$$

The network is modeled as a graph $G(V, E)$. V denotes the set of nodes in the given network and E is the set of links, including both DL and DCL. The path are weighted as $\{w_1, w_2, \dots, w_i\} i=1, \dots, k$. Our algorithms are aiming at dynamically searching for one or a set of Domain Paths, which PCEs can compute the detailed inter-domain path on.

Definition 5: Multi-Constraint Path (MCP). For a source and destination pair $\{s, d\}$ in network $N\{G\}$, MCP is formulated as

$$MCP : P_{mcp}(s, d) \leftarrow P \left\{ \sum_{l \in p} W_i(l) < C_i, i = 0, 1, \dots, k \right\} \quad (3)$$

For the additive QoS constrains, the multi-constraint path problem can be seen such as the all the QoS weights of links within the path $p\{s, d\}$ do not excess the constrains. From the definition we can see, the paths to fulfill MCP problem is not a single solution. It is obvious to tell, that there could be more than one path from source s to destination node d that all the links within them do not excess the QoS constrains.

Definition 6: Multi-Constraint Optimal Path (MCOP). For a source and destination pair $\{s, d\}$ in network $N\{G\}$, MCOP is formulated as

$$MCOP : P_{mcp}(s, d) \leftarrow P \left\{ \min \left(\sum_{l \in p} W_i(l) < C_i, i = 0, 1, \dots, k \right) \right\} \quad (4)$$

The multi-Constraint Optimal Path problem has been proved to be NP problem by previous research. However, it is still worth to investigate in this problem on the purpose to search for sub-optimal paths that compliance with all constrains, while optimize the network from some certain perspective.

The next sections are going to introduce three algorithms for multiple constrained inter-domain path computation.

4 Algorithms

In this chapter, we carry out three algorithms for computing the MCP and MCOP. The algorithms are designed to be able to apply within the PCE based inter-domain routing architecture. PCEs can execute the algorithm to calculate the domain level routing paths both for the per-domain routing and BRPC procedure. There is trade-off between the routing message overhead and performance. The decision can be made between PCEs according to Service Level Agreement (SLA), policies and any other requirements.

4.1 Link Weight in Domain Path Vector

According to the definition of MCP and MCOP, in our algorithms we consider the link weights to be additive, although not all the QoS constrains are additive. Bandwidth as an important parameter in QoS routing is not additive, but it is easier to compute MCP or MCOP with bandwidth because the not complaint links or paths can be pruned earlier before counted into the computation.

As we have noticed that it is NP hard to solve the MCOP problem, in our work we focus on search for the paths that are sub-optimal in the aspect of improving the inter-domain link utilization and reducing the connecting blocking probabilities. In the last chapter, we introduce a DPV updating mechanism with the objective of reduce the DPV routing overhead. However, this mechanism slow down the information updating between PCEs, which can cause the domain path computation less accurately compare to the ideal situation. Thus we compensate the update lagging by a dynamic path length computation formula.

One of the easy and most considered way to compute path weight is to give a fixed weight to the given constrains as shown in (5). For the light loaded network, formula (5) is suitable with a set of well

designed parameters α_i , $i = 0, 1, 2, \dots, k$. For the network with irregular traffic pattern, formula (5) can not reflect the loading condition simultaneously.

$$W(s, d) \leftarrow \sum_{l \in p} \alpha_l w_l \quad i = 0, 1, \dots, k \quad (5)$$

Thus, we consider a path weight that can reflect the network traffic condition. Formula (6) is a dynamic link weight that we are going to use in the following algorithms. In this formula, the link weight is the function of U_{ij} – the current utilization of the link bandwidth.

$$\begin{aligned} C(U_{ij}) &= C(\Delta)U_{ij} + 1 \quad \text{if } U_{ij} \leq \Delta \\ C(U_{ij}) &= C(\Delta) \frac{\Delta}{1 - U_{ij}} \quad \text{otherwise} \end{aligned} \quad (6)$$

Formula (6) divides the computation of weighted links into two different stages. When the link utilization is under a certain bound, the link weight can be seen rising linearly together with its own utilization. As soon as the link utilization is beyond the bound, the weight of the link is not linear growing anymore. Instead, it is defined as the second part of formula (6). In this case the link weight of the heavily loaded link grows much faster than the light loaded link.

4.2 DDP algorithm

To introduce the computation of domain level routing path, we start from a basic algorithm which is based on Dijkstra algorithm but with modification:

- The result list `dp_list` contains only the (sub-) paths end with destinations.
- The extended path weights consist of two parts domain link and domain connecting link. The weight of DCL varies according to the adjacent nodes.

Dynamic Domain Path (DDP) algorithm gives one exact domain path every time when it is executed.

```

function DDP (G, s, d, W)

    G = (V, E)
    s: source domain
    d: destination domain
    W: constrains associated to the links
  
```

```

1  x ← s
2  for adj [x][k], k = 0, 1.. m
3      D(adj[x][k]) ← l{x, adj[x][k]}
4      cand_path ← p{x,k}
5      prev[x] ← x
6  end for
7  while cand_path is not empty
8      p{x,i} ← remove(cand_path)
9      If i == t // destination
10         Insert(dp_list, p{x,i})
11         goto 7
12     end if

13     for j = i's adj[i][k] k = 0, 1, ...m
14         && adj[x][k] != prev[i]
15         dist(j) ← W(p{x,i}) + W(l{x, prev[x], j} ) + W(l {i, j})
16         cand_path ← sorted_insert(p(x), dist(j))
17     end for
18 end while
  
```

Figure 4-1 algorithm of DDP

The pseudo code of algorithm DDP is given in Figure 4-1. The analysis is as follow:

Initialization: line 1—6

The initialization part initializes the list of candidate paths (cand_path) with the $p\{x,k\}$, the path between source and its adjacent nodes.

Path relaxation: line 7—12

This part of pseudo code checks the shortest sub-path stored in cand_path. If the end node is one of the destination nodes the sub-path is removed from cand_path.

Path extending: line 13-18

The current examined path $p\{x, i\}$ is extended to node i 's adjacent nodes. Adjacent nodes of i can not appear in $p\{x, i\}$ to avoid the loop. The new weight of extended path is computed in line 14. If the weight of $p\{x, j\}$ is shorter than the previous stored one, the new path replaces the previous one. As we have indicated at the beginning of the section. The weights of DCL are normally different depending on the adjacent nodes.

As we can see from the description of the algorithm, there is only one path for each source and destination pair. DDP can solve the MCP problem but not KMCP. It is suitable for the PCE based routing that requires low overhead and fast reaction. However, it cannot provide BRPC procedure with more than one domain level path which is a limitation of this algorithm.

4.3 MK-DDP algorithm (with dynamic link length, multiple constraints)

DDP algorithm gives one exact domain path every time it is executed. However it does not cover the situation that BRPC procedure requires more than one domain level path when it is necessary. In this Multi-constraint K shortest Dynamic Domain Path (MK-DDP) algorithm, there are more than one DPs are returned for the use of BRPC.

There are several issues stemming from the KMCOP algorithm design. First it requires more computation resource for storing the K shortest path and the sub-paths during the computation. Second an efficient online searching procedure or offline computing stage is needed for carrying out the results on time. Moreover, it also lacks an additional selection process to choose K shortest path out of all the candidates.

```

function MK-DDP (G, s, d, W)

    G = (V, E)
    s: source domain
    d: destination domain
    W: constrains associated to the links

```

```

1   for neighbour[x][k], k = 0, 1.. m
2       D(neighbour[x][k]) ← l{x, neighbour[x][k]}
3       cand_path ← p{x,k}
4       prev[x] ← x
5   end for

6   while cand_path is not empty
7       p{x,i} ← remove(cand_path)
8       If i == t // destination
9           Insert(dp_list, p{x,i})
10          goto 7
11      end if

12     for j = i's neighbour[i][k] k = 0, 1, ...m
13         && neighbour[x][k] != prev[i]
14         dist(j) ← W(p{x,i}) + W(l{x, prev[x], j}) + W(l {i, j})
15         If dist(j) is_not_dominated
16             cand_path ← sorted_insert(p(x), dist(j))
17         end if
18     end for
19 end while

```

Figure 4-2 MK-DDP algorithm

As it is obvious that not all the sub-paths that algorithm searches are going to be one of the K shortest candidates, thus it is more efficient to reduce the computation storage size by excluding some of the sub-paths during the computation. There are several previous works such as [37] and [44] that use the concept of path dominance to exclude some of the paths that are considered will definitely be excluded in further process.

Definition 4: DOPinated Path (DOP), there are two DP $p = \{s, d\}$, $q = \{s, d\}$, they have QoS matrix $a = \{a_1, a_2, \dots, a_k\}$, and $b = \{b_1, b_2, \dots, b_k\}$, thus, for all $i = 1, 2, \dots, k$, $a_i > b_i$, it is called p is dominated by q or q dominates p .

The definition of DOP defines a set of sub-paths that has determined to be excluded further. So it is better to remove them from the candidate list as early as possible to make the procedure execution time shorter and less complex. However, the algorithm also needs to make sure there are at least K shortest paths that are carried out. So the sorting and removing process will only be executed when there are more than K sub-paths are stored in the candidate list. If there is no paths that are dominated by others, we can apply some policies to make the tie breaking. The algorithm MK-DDP is explained as follow:

Initialization: line 1—5

The initialization part initializes the list of candidate paths (`cand_path`) with the $p\{x, k\}$ – the path between source node and its adjacent nodes.

Path relaxation: line 6—11

This part of pseudo code checks the shortest sub-path stored in `cand_path`. If the end node is one of the destination nodes the sub-path is removed from `cand_path` and inserted into `dp_list`.

Path extending: line 13-18

The current examined path $p\{x, i\}$ is extended to node i 's adjacent nodes. Adjacent nodes of i can not appear in $p\{x, i\}$ to avoid the loop. The new weight of extended path is computed in line 13 and 14. After the new weight computer, a function Dominated-Remove is executed to check if the new path is dominated within the `cand_path`. The new sub path can only be stored only if it is not dominated by any previous paths.

4.4 A*-Dominated algorithm

4.4.1 Motivation

In the two mathematic algorithms described above, we abstract the network into abstract graphs and the mathematic model is established based on the exact attributes information of nodes and edges. These methods achieve the solution of MCOP or KMCOP with the concern of the network resource optimization than the algorithm feasibility and complexity. The heuristic approach, on the other side, uses special information to improve the computational efficiency. [45] carries out the A* algorithm that computing the shortest path with heuristic way. A heuristic algorithm based on A* is proposed here to give an alternative solution in computing the dynamic domain level path. Different from the above two algorithms, this heuristic algorithm is based on source routing, that is, it requires less from the link state information.

4.4.2 A* and A*-Prune

The A* algorithm is proposed based on the below definitions. The main idea is to draw together the mathematic and heuristic approaches together for an improved computational efficiency.

Definition 7: projected length, given a path $p \{s, i\}$, that start from source node s and end by an intermediate node i , the projected length of this path is

$$H_i(s, d) \leftarrow W\{s, i\} + A\{i, t\} \quad (7)$$

Definition 8: admissible path, given a path $p \{s, i\}$, that start from source node s and end by an intermediate node i , the path is admissible if

$$H_i(s, d) < \overline{H}(s, d) \quad (8)$$

As we have analysed in the section of related work A*-Prune algorithm designs a heuristic algorithm to solve the KMCOP problem.

It reduces the computation storage and accelerates the speed by pruning the inadmissible sub-paths.

4.4.3 A-Dominated algorithm for source routing*

The algorithm we proposed here is based on A* algorithm but with improvement in several ways:

- The dominance of sub-paths are checked every time before they are inserted into the candidate paths list.
- The admissible distance is computed according to DPV.

The detailed explanation of the algorithms is:

Initialization: line 1

The initialization part initializes the list of candidate paths (cand_path) with the $p\{x,k\}$ – the path between source node and its adjacent nodes.

Path relaxation: line 2-7

This part of pseudo code checks the shortest sub-path stored in cand_path. If the end node is one of the destination nodes the sub-path is removed from cand_path and inserted into dp_list.

Path admission: line 8-15

The current examined path $p\{x, i\}$ is extended to node i 's adjacent nodes. Adjacent nodes of i can not appear in $p\{x, i\}$ to avoid the loop. The projected distance is computed in line 9. If the path is admissible it is inserted into the candidate list cand_path, else it will be discarded. After the new weight computer, a function Dominated-Remove is executed to check if the new path is dominated within the cand_path. The new sub path can only be stored only if it is not dominated by any previous paths.

Function A*-Dominated

$G = (V, E)$

s: source domain

d: destination domain

W: constrains associated to the links

```
1  for neighbour[x][k], k = 0,1...m
    insert (cand_path, p{x,k})
end for

2  while cand_path is not empty
3    p(x,i) ← remove(cand_path)
4    if i == t
5      insert (dp_list, p(x,i))
6      goto 3
7    end if

8    for j ← neighbor[i][k] , k = 0,1,...
9      if  $Wr(p(x,j)) + Hr(p(j,t)) < Cr(x, t)$   r = 1, 2, ...R
10       insert(cand_path, p(x))
11       Dominated_Remove(cand_path)
12     end if
13   end for
14   Dominated_Remove(dp_list)
15 end while
```

Figure 4-3 A*-Dominated algorithm

Function Dominated_Remove(dp_list, i)

 for $p(s,i) \leftarrow dp_list[i][k]$ $k = 1, 2 \dots n$

 if $p(s,i)$ is dominated

 remove(dp_list, i)

 end if

 end for

 return

Chapter 5 Next Generation Network control plane and testbed

1 Introduction

With the emerging of highly demanding network services typically IPTV transport, network carriers are working hard to provide their transport network services with the carrier-class attributes such as assured end-to-end service of quality, large scalability and stable reliability, in the mean time, low cost and simple maintenance.

ITU-T IPTV and NGN focus groups at the same time have been working for years to develop the NGN architecture that provides a framework that allowing the delivering of network transport services. And it is now widely accepted that the Internet Protocol (IP) will form the basis for new services, as well as assist in the transition of circuit-based services to packet-based services (e.g. Voice and Video over IP). However, it is far from certain that IP routing technology will be adopted as the transport convergence layer. IP/MPLS has been widely deployed, especially in carrier backbone/core networks as a service layer and as a convergence layer, but Ethernet is fast becoming a credible alternative candidate. 95% of all data traffic either originates or terminates at Ethernet, and the data volume is forecast to grow tremendously given the impact of new video services and IPTV for

example. This situation has prompted many telecom carriers to consider Ethernet as a potential convergence solution for NGN. With its scalability, ubiquity and natural support for IP services, Ethernet provides a compelling case. But before Ethernet can be adopted, it must be capable of supporting multiple services with at least the same level of quality as existing carrier services. In other words, Ethernet services must achieve a carrier-class of quality.

MEF brought out the Carrier Ethernet concept by means of adding the carrier-class services attributes on to the conventional Ethernet services. According to MEF, a Carrier Ethernet service and the underlying equipment supporting the service must possess the following attributes: Standardized services, Scalability, Reliability, Quality of Service and Service management.

As a response to the increased interest in providing high performance network for delivering IPTV traffic, the HIPT project was founded with the objective of enhancing the carrier Ethernet transport for IPTV applications by developing technology that can fulfill the increasing requirements in terms of bandwidth and quality and at the same time reduce cost of network operation. As a phase toward the objective, a test bed based on the Carrier Ethernet is designed and built up for the purpose in providing a testing environment to optimize the IPTV transport network.

2 Architecture Design

The data services movement from the conventional voice services to the multimedia and video services gives great motivation to choose Carrier Ethernet as an important candidate of convergence services in the area of metro transport network. The SDH/SONET and ATM transport infrastructure which are dominating in this area before, however, cannot scale to support the rapid growth of the packet-switching data traffic in a cost effective manner. One of the SONET/SDH major limitations is the lack of flexibility and manageability in granularity of bandwidth so that smaller streams of traffic to the needs of individuals and enterprises cannot be managed through.

In another side, in the IP world, the IP/MPLS has been widely accepted in the area of core network. However, the IP based routing and signaling working mechanisms during the procedures such as routes discovery, resource reservation and network management gives a big limitation on the efficiency to precede the carrier-grade services. Thus in HIPT, we investigate on carrying out a layer 2 Carrier Ethernet transport network architecture complied with Next Generation Network framework (Fig.4-1).

Fig.1 is a NGN based transport network architecture which is provisioned by three function blocks: Service Control Functions (Service Control Function (Service Control Function in Fig.4-1), transport network control plane (RACF in Fig. 4-1) and transfer functions (Layer 2 transport network in Fig.4-1). The architecture design scheme and mechanism are adopted with the ITU-T NGN architecture.

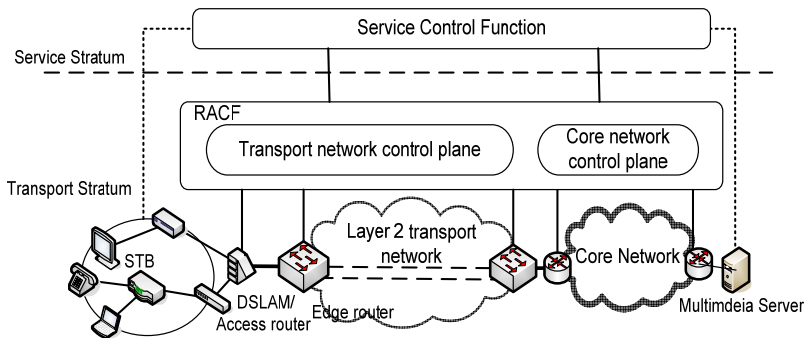


Figure 5-1 Carrier Ethernet transport network architecture based on NGN architecture

Carrier Ethernet resides in the lowest block of Layer 2 transport network. Due to the cost-efficiency and scalability limitations described at the beginning of this section, the Layer 3 dynamic routing in the metro/access domain is replaced by a scalable architecture with static tunnels by means of PBB-TE or MPLS TP. According to the NGN architecture, there is centralized transport control plane above the transfer functions which deals with all the issues of transport network resource control and management. In Fig.1 this control plane

refers to RACF (Resource Admission Control Functions) as the same name in. The functions in the Service Control Function block are within network Service Stratum which is not connected directly to the transport network. It is located in the network service layer and deals with the application layer signaling, resource reservation negotiation, access authentication and accounting etc.

The following subsections are going to present and describe about this Carrier Ethernet transport network according to Figure 5-1.

3 Control Plane Architecture for MPLS TE

3.1 Requirements

The resource and admission control functions (RACF) in NGN control plane is specified by ITU-T recommendation Y.2111. As described above, the transfer functions in the NGN transport layer just concern the data conveyance from one point to another, thus the RACF takes responsibilities of all the related admission and control functions. It can also be considered as a tie connecting the service and transport network, and transforming the information exchanged between them.

The NGN framework proposed by ITU-T (recommendation Y.2001, Y.2011) brings in an evolutionary functionality division methodology. The idea of the function division in the NGN is to keep the diversity of the existing network services and technologies while decomposes its architecture into horizontal and vertical two dimensions. The purpose is to declare the independent roles on network control and transport functions. The set of transport functions reside in NGN transport stratum are merely concerning with the packets conveyance and leave the control plane with all of the functions related to the network resource control and management.

In NGN, this control plane is visualized to the Resource and admission control functions (RACF) and Network attachment control functions (NACF). There are function blocks related to the service control (e.g. user authentication, user profile management, service admission control etc.) and function blocks taking the charges of the

transport network(s) control (e.g. access admission control, network resource/policy control, dynamic connectivity provision etc.) as well. Differ from traditional control plane distribution scheme, one of the advanced aspects of this NGN control plane is the logically integrated and physically distributed functional components. Unlike the IP/MPLS distributing its control functions in every switch component in the transport layer, RACF gathers all the tasks about transport resource control into one system to keep the simplicity of the transport network. However, the features of unified, standardized and underlying technology agnostics of the NGN control plane make it suitable to all kinds of transport networks and the distributed control components keeps the data delivery seamless and flexible.

4 Functional architecture design

The resource and admission control functions (RACF) in NGN control plane is specified by ITU-T recommendation Y.2111. As described above, the transfer functions in the NGN transport layer just concern the data conveyance from one point to another, thus the RACF takes responsibilities of all the related admission and control functions. It can also be considered as a tie connecting the service and transport network, and transforming the information exchanged between them.

Fig 1 is a simple Carrier Ethernet solution with the control plane based on NGN. In the RACF block, two main function entities PD-FE (entities policy decision function entity) and TRC-FC (transport resource control function) perform the technology independent and technology dependent network resource control respectively. The PD-FE provides a single contact point between the service stratum and the transport stratum. [3] It hides the underlying transport technologies for the service control functions (SCF) and it is technology independent as well. All the final policy decisions are made here with the consulting to the TRC-FE (Transport resource control function entity) for the technology dependent information such as the network resource availability held by the instances in TRC-FE. After making the decision, the policy is also pushed down to the accordingly policy enforcement function entity (PE-FE) in the transport network.

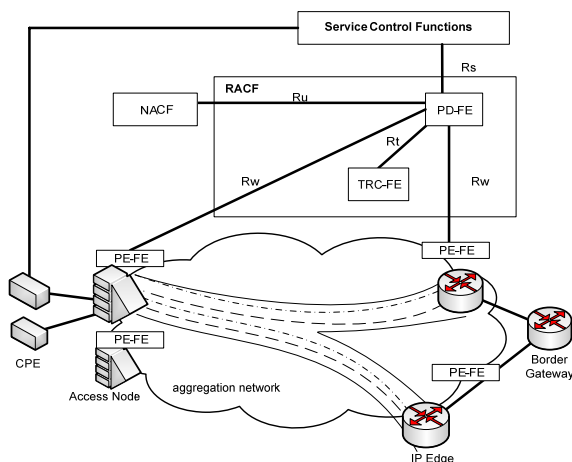


Figure 5-3 Carrier Ethernet with control plane based on NGN

Considering the T-MPLS based Carrier Ethernet scenario, the functions executed inside the PD-FE will not make difference, however the TRC-FC has to keep a specific instance that aiming for this T-MPLS based transport network. According to the specific requirements of the T-MPLS realized carrier class Ethernet transport network, the TRC-FC should perform the following functions:

- Transport network topology and link capacity maintenance.
- Call and admission control (CAC).
- Technology dependent QoS requirement and attributes mapping from service level to network level.

The policy enforcement function entities (PE-FE) residing in the edge devices at the T-MPLS network should perform the following functions:

- Flow based traffic policing and shaping.
- T-MPLS label distribution.

5 QoS class mapping and policing

To achieve the QoS transport, the RACF in the control plane should map the QoS requirements from the application level to the transport level and push them as flow based policy down to the correspondent PE-FE (policy enforcement function entity). The transport network should refer to this policy information and perform the correspondent transfer behaviours to different traffic flows. This paper illustrates the schemes on the QoS maps taking place between the T-MPLS control and transfer functions. It also carried out a double label scheme on T-MPLS based transport network which using double labels to carry the information such as policy and service priority during packets transport.

The mapping between the SCF (service control functions) and the PD-FE (policy decision function entity) is underlying technology independent; there is no need to specify a scenario for Carrier Ethernet.

Upon receiving the request from the service layer, the PD-FE will do the resource availability check by inquiring the related TRC-FE and try to install the policy into the correspondent underlying routers. To achieve the QoS transport and flow based policy in the T-MPLS transport layer, two identifiers are needed to associate with one traffic flow: the service/user ID and the flow ID. The former one will be treated as the indicator to both the LSP to the destination and the service class. As illustrated in Fig. 3, the thick grey tunnels are the LSPs designating to difference service classes. The service IDs are gained from the PD-FE according to the service level QoS requirements. The latter one can be used as the indicator for traffic policing at the edge routers. In Fig. 5-3, they stand for the thin tubes inside the LSPs.

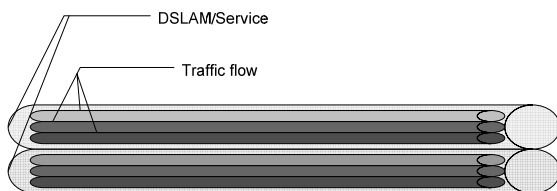


Figure 5-4 T-MPLS double label scheme

In the T-MPLS based transport network, these two IDs will be mapped into two labels in every packet, as shown in Fig.5-4.

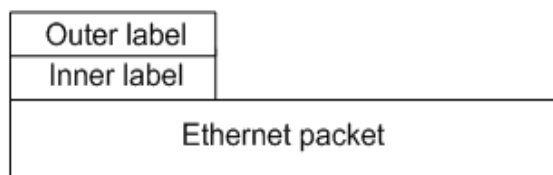


Figure 5-4 Double label scheme

6 Carrier Ethernet Test bed implementation

In order to approach more Carrier Ethernet research for HIPT project and reflect the status results on time. We built up the Carrier Ethernet test bed according to the Carrier Ethernet architecture we designed in the second section. Thus, a series of traffic performance test can be carried out within this test bed.

Fig.4 is the architecture that has been implemented in this Carrier Ethernet test bed. It is compliance with the architecture in Fig.1 and the functionalities are all compliance with the description in section. The following subsections will present the test bed from the facilities, working procedures and demo results.

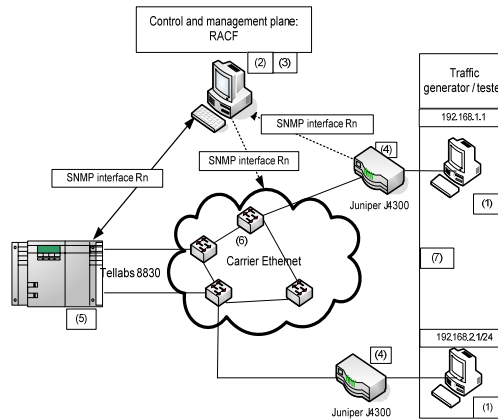


Figure 5-5 Test bed implementation

6.1 Test bed facilities

Table 1 lists the equipments facilities for this Carrier Ethernet. The numbers following the function components name point out the component location in Fig.4. The description of each function component is given in the next subsection.

Table 5-1 Test bed facility

Function component	Equipment
Area border router (5)	Tellabs 8830 Multi-service router
Access router (4)	Juniper 4300
CE switch (6)	Tpack Carrier Ethernet demo box
Traffic generator	Aligent traffic generator

6.2 Functional components

In section, it gives a brief description of the working scheme inside this Carrier Ethernet. In this section, we will give out the functions being implemented inside every function components inside this test bed.

(1) CPE: in this experimental network work as network service client. They locate as the end users behind the MPLS label edge router. It initiates network service requests with SIP signaling protocol. Based on SIP syntax, the service requests explicit different service classes and bandwidth requirements.

(2) Service Control Functions: As a SIP server, it analysis and routes the incoming SIP messages to the recipients. As part of the NGN transport network functions. SCF communicates with the network control plane to deal with the application level QoS negotiation.

(3) RACF: this function component emulates the functions as defined in NGN control plane RACF. The resource admission control functions are resides in this plane such as PD-FE, TRC-FE. According to the network request, Control plane communicates with Carrier Ethernet equipments to push the policy and QoS parameters to config LSPs along the MPLS TP tunnels and get the network statistics through interface Rn.

(4) Edge router: 2 Juniper J4300 MPLS router are configured with LSPs of different service classes and represent as MPLS TP edge router.

(5) Area Border Router: As the border router, it can be seen as an extension point between both the control plane and other AS. It deals with the traffic policy control.

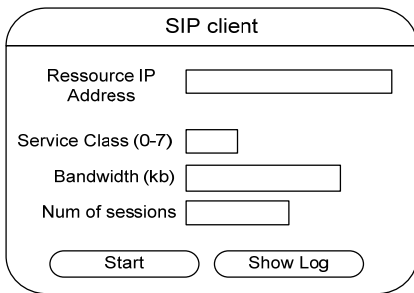
(6) Carrier Ethernet MPLS TP Switches: this CE supported switch is designed to provide switching within carrier-class. It supports up to 3 pushes and 3 pops per packet; MPLS TP OAM and LSP protection in hardware level. It receives the QoS and policy configuration command from RACF, thus each flow can be mapped to a separate output queue. It also supports the MEF bandwidth profile: <CIR, CBS, EIR, CF, CM>.

(7) Traffic generator and tester: It works as a service content provider or simulated VoIP client. It generates traffic with the parameters (traffic load, packet length, packets contents) configured according to the services it is required.

6.3 Working procedures

The working procedures within this Carrier Ethernet test bed loosely following the working procedures introduced by ITU-T's NGN recommendation. Before the session starts, each CE switch and edge router is configured manually with the MPLS LSP QoS and policy mapping information.

This test bed provides a JAVA simulated SIP client user interface (Fig. 5-6) from which user can customize the different scenarios by choosing the different destination IP addresses, service classes and bandwidths.



The diagram shows a user interface window titled "SIP client". Inside the window, there are four input fields with labels: "Ressource IP Address", "Service Class (0-7)", "Bandwidth (kb)", and "Num of sessions". Below these fields are two buttons: "Start" and "Show Log".

Figure 5-6 SIP client user interface

In this test bed SIP client, More than one session can be set up simultaneously from one SIP client by specifying more than one session from the user interface.

After the session was triggered, a SIP based QoS service signaling goes between the two CPEs and service control functions. JAVA socket wrapped SIP based signaling carries on the session parameters of the ones input from the user interface. Upon receiving the request, Service control functions will invoke the RACF functions which are in charge of making the resource reservation decision according to the knowledge managed by RACF functions component.

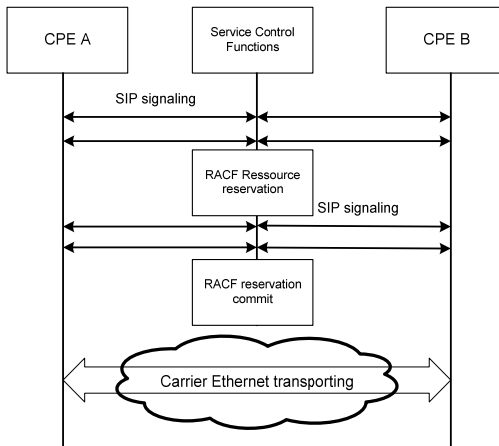


Figure 5-7 Resource reservation and commit procedure

The knowledge such as network topology and network resource is obtained by RACF function component by means of SNMP protocol through interface Rn. A JAVA API SNMP4J is used here as communication tool between the transport equipments and control function RACF server. By the end of a successful SIP signaling, RACF will commit its final resource reservation decision down to the edge Carrier Ethernet switches. This policy pushing is also by means of SNMP4J API. Thus, the QoS information interpreted through Service Control Functions and RACF function components are finally pushed into the CE devices: Carrier Ethernet switches. In another word, until now, the SIP based session information is conversed into flow-based traffic parameters; each session is identified with a unique ID which is assigned at the beginning of the session initialization, and by this step, the session ID is mapped into a unique flow ID (Fig. 5-8)

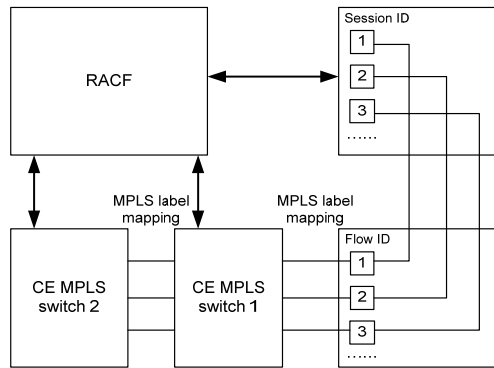


Figure 5-8 Carrier Ethernet QoS and LSP mapping procedure

In our test bed the Carrier Ethernet MPLS switches support multiple ways of identifying the unique traffic flow. The unique flow ID can be derived from MPLS EXP bits, VLAN priority bits or IP DS bits. After receiving the policy parameters, all the CE switches will push the according MPLS label by checking the flow ID. Thus, the traffic flows can be treated classified.

7 Result Analysis

7.1 Control plane simulation

To illustrate the feasibility and possibility in realizing the Carrier Ethernet based on NGN, a Carrier Ethernet model implemented by OPNET (Fig. 5) is built here. Inside the model two scenarios are built: the admission control functions in the control plane with or without CAC function. The collected traffic statistics (end-to-end delay) and the comparison can be seen as a demonstration to the control plane influence to the transport network.

All the technologies and the concept described above are simulated into this model, including the separation of the control and transfer functions, the T-MPLS QoS transport functions (traffic policing and queuing), the QoS signaling and mapping from service level to the

transport level and the call and admission control (CAC) inside the control plane.

All the nodes including the network ingress node, switches, area border router and the control plane (RACF) here are implemented with technologies described above. The end users running the VoIP, VoD and HTTP applications are placed in the access part of the transport network behind the ingress switch with the computer icon. The ingress node is the access node or can be treated as the DSLAM between the access network and the transport network. After the ingress node, there are the T-MPLS enabled switches, which form the T-MPLS metro network. The traffic is aggregated and switched through these switches. The nodes named “RACF” and “service center” reside at the other end of the transport network which can be seen as the core network. Node RACF plays the same role as the RACF in NGN. The node “service center” is the aggregation of the P-CSCF proxy and the RTSP proxy serving the SIP, RTSP (Real Time Streaming Protocol) and signaling.

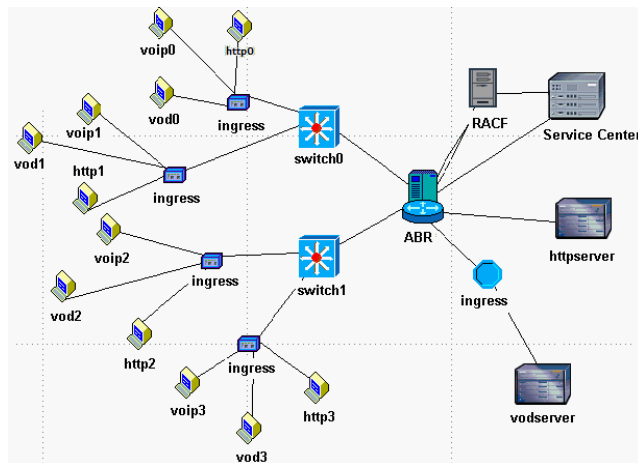


Figure 5-9. OPNET model for Carrier Ethernet with control plane

Fig. 6 is the end-to-end delay of the scenario without CAC. The VoD application is set to send the data exceed the network resource reservation. From the figure we can see, as long as the transport policy gateway (token bucket) is working, the whole network is not totally

corrupted with the “criminal bandwidth abusing”. However, the two “hills” in the VoD packets delay shows the instability in the network without CAC. The network transport environment could be easily crashed by some “illegal” behavior such as trying to occupy a big amount of bandwidth.

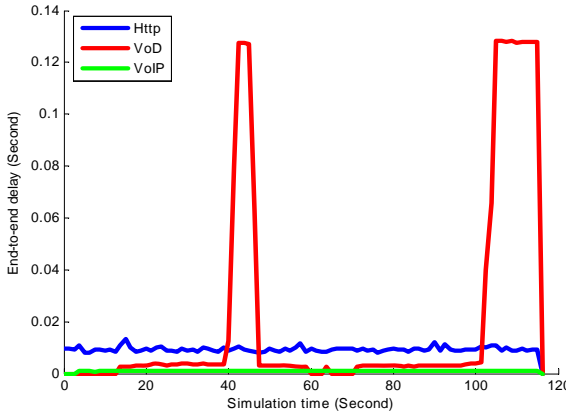


Fig. 6. End to end delay without CAC

However, under the simulating same conditions as the prior scenario, the situation will be different in the network with CAC function. Fig. 7 shows the simulation results for the transport network with CAC.

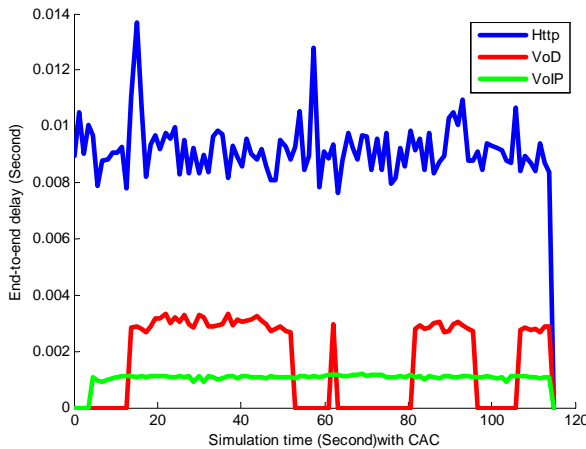


Fig. 7. End to end delay with CAC

The lags in the vod delay plot imply rejecting periods when there is not sufficient resource decided by the TRC-FE. Until the network gets the enough resource for the vod application, the following requests will be granted which is shown as the latter part of the red plot in Fig. 7. Additionally, the three plots in both the two scenarios also imply the different QoS service priority in the three applications. The VoIP has the highest priority while the Http has the lowest.

7.2 Test bed

7.2.1 Flow based QoS switching

Since this NGN based Carrier Ethernet architecture has been verified at a simulating research which the results have been published in another paper. Thus, this architecture will be proved at emulating level within this test bed. We designed a test scenario based on the QoS traffic transport performance evaluation. The traffic generator will generator 3 traffic flows with the different IP address which indicating the different service class within the Carrier Ethernet network. All the three flows will be switch through the network as in Fig. 4 and be received by the traffic generator, where the classified service performance will be tested.

Thus, according to the working procedure in the last section, three LSP indicating the different service class and bandwidth profile will also be set up.

The bandwidth provision for the service classes and LSP bandwidth profile in Table 5-2 and Table 5-3 are compliance with the double label scheme we proposed in the Carrier Ethernet transport network section. The outer label indicates the service class as mentioned in Table 2, and the bandwidth profile for each flow is decided in Table 5-3.

Table 5-2 service class provision

Service class	Ban dwidth (Kpbs)
0	4900
1	4900
2	4900
3	4900

Table 5-3 LSP bandwidth profile

Flow	Bandwidth profile
RT (class 0)	Peak data rate: 4000 k Committed data rate: 4000 k
Video (class 2)	Peak data rate: 4000 k
BestEffort (class3)	No committed data rate

Figure 5-10 contains three plots: Seq Errors counts the sequence number error for every incoming packet in each traffic flow; Tx Test Throughput shows the traffic throughput coming out from the traffic generator and the Rx Test Throughput shows the flows throughput incoming.

From these three plots we can well tell, that the flow with highest service class (RT) can always get the assurance under their committed data rate which the lowest one (BestEffort) is always be sacrificed. In the “hill” part of the second and the third plots, the Tx and Rx throughput has the same trend but different scale. The BestEffort traffic has to be dropped to make the other two flows keep their committed bandwidth profile. However from the Seq Errors plot we can also see the packets dropping from the two higher classes, that is because the total bandwidth far exceeds the total bandwidth provision for the certain service classes. The in total bandwidth consumption is beyond the capacity of the network, so the even the first class traffic need to be dropped.

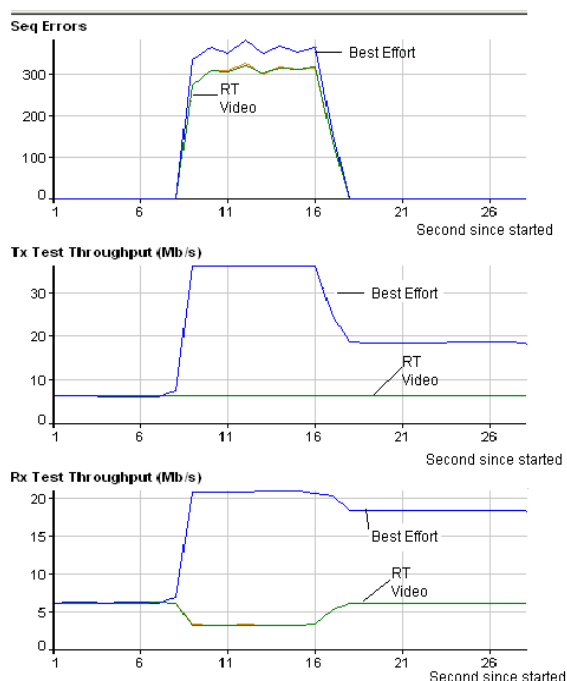


Figure 5-10 Traffic classified performance and throughput

7.2.2 PBB-TE resilience

The goal of this part is to evaluate the reliability of the carrier grade PBB TE transport network. In this experiment, we set up PBB TE working path and its protection path with TPACK Longmorn switch as shown in figure 5-11. The Longmorn switch is configured as three logical switches. These three switches is physically located in one switch but logically independent. These two PBB TE paths are established upon these three switches. One is seen as working path (solid line) while the other is protection (dashed line). The PBB tunnels are defined within the working and protection paths. These two tunnels can be seen as Carrier Ethernet transport network.

IPTV server connecting to one end of the working paths continuously sends High Definition (HD) video through the working tunnel. To evaluate the reliability of this carrier Ethernet transport network, we use the parameter Media Delivery Index (MDI). MDI comprises two

factors: Delay Factor (DF) and Media Loss Rate (MLR). They are measurements of the quality for a transport network.

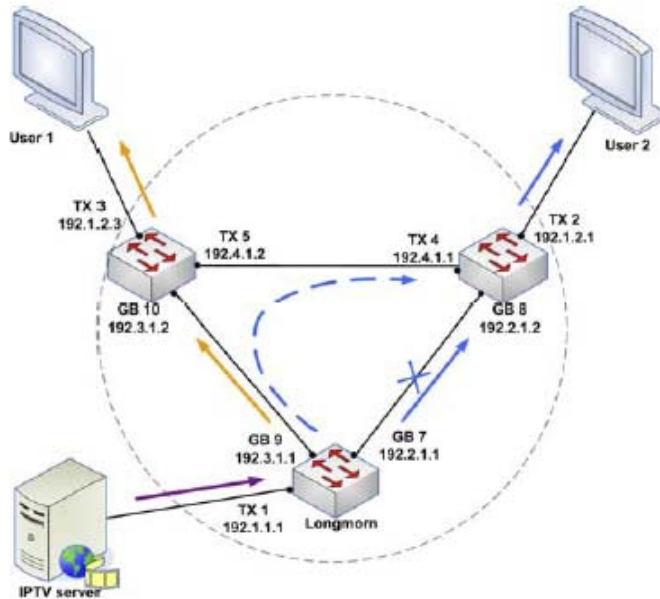


Figure 5-11 PBB-TE working and backup path

To evaluate the resilience of this Carrier Ethernet, we measure MDI under different OAM interval times. The OAM parameters settings are shown in Figure 5-12. Here we specifically evaluate the values 3 ms, 10 ms, 100 ms and 1 s. The Aglient N2X traffic tester is connected to the network to measure the MDI values.

For the demonstration limitation, we cannot illustrate the video quality by which way better than description. Table 5-4 shows the subjective evaluation with different OAM update intervals.

Properties for PBT tunnel

PBT Interface: Ethernet (GB 8)

Local Address: 00:00:00:00:00:08

Remote Address: 00:00:00:00:00:07

VLAN ID: 100

☐ MPLS interface

☒ Enable CFM

CFM MD

MD: MD 1

CFM MA

MA name: mal

CCM Interval: 10ms

CFM MEP

☒ Active ☒ CCI

Local MEP ID: 8

Remote MEP ID: 7

CCM LTM Priority: 0

Lowest Priority Defect: macRemErrXcon

Fault Alarm Time: 250

Fault Alarm Reset Time: 1000

OK Cancel

Figure 5-12 OAM interface

Table 5-4 Subjective evaluation

Update Interval	Comments
1 sec	Long breaks and it seems that the stream loses synchronisation. Definitely not acceptable.
100 msec	Often this induces breaks in the stream, and severe artifacts are present. The result depends on the failure time with respect to the MPEG stream. The quality is not acceptable
10 msec	Minor artifacts observed. Rarely loss of sync or frames. Acceptable
3 msec	Very few artifacts. Definitely acceptable

Figure 5-13, 5-14, 5-15 and 5-16 depict the MDI values for the four different OAM update intervals. From these four figures we can see, there are two peaks in each plot. The first peak shows the moment for failure happen and the second one happens when the restoration takes place. The working path is determined fail when three OAM frames are lost. In this way, the less update interval results to smaller MDI value.

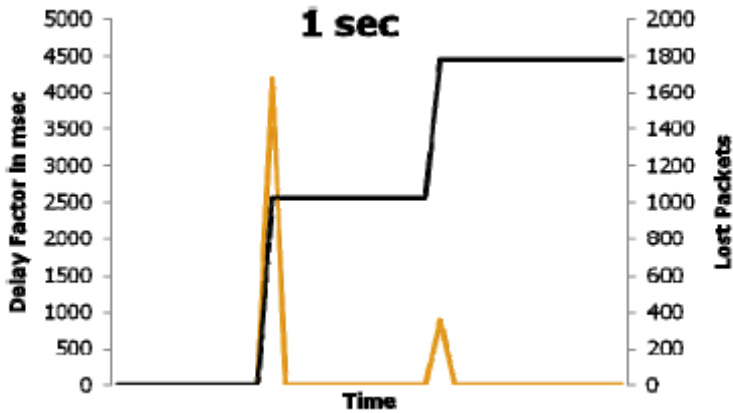


Figure 5-13 MDI for 1 second update interval

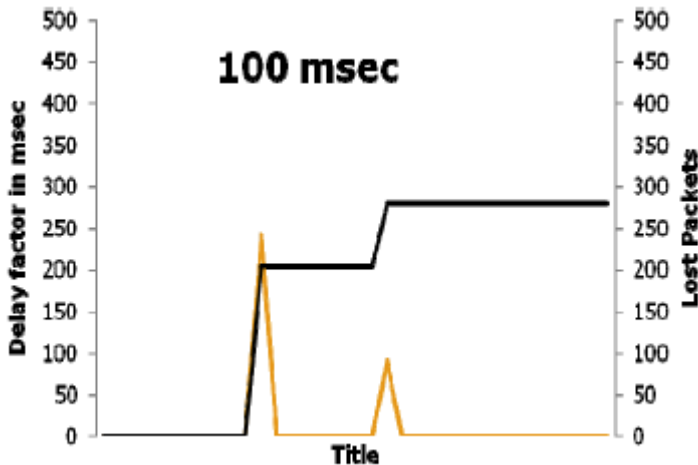


Figure 5-14 MDI for 100 msec update interval

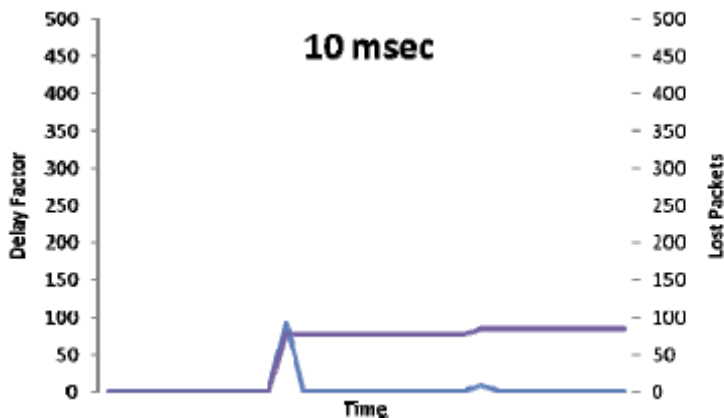


Figure 5-15 MDI for 10 msec update interval

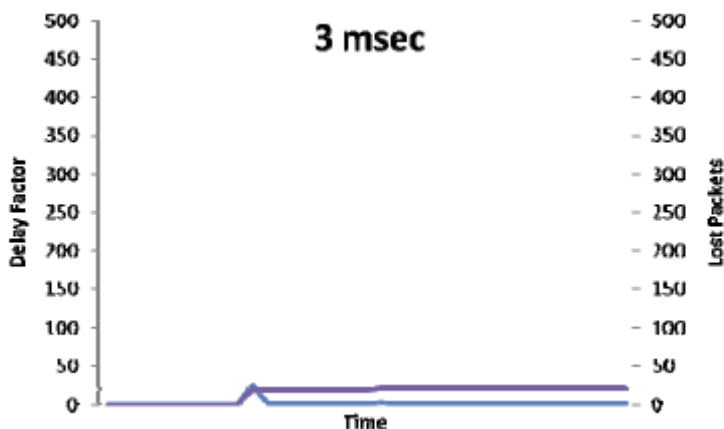


Figure 5-16 MDI for 3 msec update interval

The results and the subjective evaluation indicates that a service provider, who plans to use a Carrier Ethernet for providing IPTV services should use an OAM update interval of no more than 10 ms to ensure his customers an acceptable quality even in case of failures. Should he also provide interactive services, it might even be relevant to lower the interval to 3 ms, as this has a dramatic impact on the MDI quality measure.

8 Conclusion

In this chapter we have discussed the future services in the internet with special focus on the Metro Network. We evaluated the expected future services, which we classified according to their network requirements. Then we chose IPTV as a representative candidate, and we showed how a Carrier Ethernet can be operated to support such application. Finally, we provided a subjective evaluation backed by MDI measurements to define the most optimal OAM update frequency for such application in a specific PBT enable Carrier Ethernet setup. It was indicated that an OAM update interval no longer than 10 ms provides acceptable user perceived quality.

Chapter 6 Conclusion and future work

1 Summary

This thesis presents the work in enhanced inter-domain routing protocol, algorithm and NGN based control plane for resource admission.

The DPV enhanced inter-domain routing protocol together with the PCE based routing architecture provides a mechanism for dynamic domain path computation. In this way, the network transporting resource utilization is more optimized. It also fills the space for the BRPC mechanism with dynamic domain sequence. The OPNET simulation shows that the enhanced protocol and routing architecture do improve the traffic engineering performance by reducing the blocking rates and increasing the resource utilization.

The three algorithms are proposed with the purpose to compute the domain path more precisely. Instead of using the Dijkstra algorithm to compute the domain level path, PCEs is implemented with advanced algorithms other than Dijkstra to compute the domain level path. In this way, it accelerates the computation execution time and optimizes the network usage more. More important, multiple constraints are taken into account instead of single constraints.

The last part of this thesis presents control plane and test bed for next generation network. The NGN based control plane controls the resource admission for MPLS network. A double label tunnelling scheme is proposed in order to traffic engineering the entire network with more granularities and larger scalability. The results from simulation illustrate that the control plane improve the performance of the MPLS transport network. The test bed of the network is implemented for presenting the performance of the carrier Ethernet from the aspects of QoS service, failure protection and traffic engineering. The results show that the transport network implemented by MPLS TP achieves the goal of Carrier Ethernet from the protection time and traffic engineering.

2 Future Research

This Carrier Ethernet test bed has just been through its first stage, only basic Carrier Ethernet transport functions are set up and emulated. However, it is not enough to be able to carry the IPTV traffic with the end-to-end QoS under the basic transport functions and control mechanisms. Here we propose two study points we are working on.

With the IPTV services, the viewers will directly experience the quality of the network, thus it is very important that the network delivers carrier-class quality of service. The networks do not deliver the required OAM functionalities and IPTV operators are forced to deploy very expensive solutions to monitor the TV signals. MPLS network OAM is specific to the transport network and functionality is referenced from ITU-T's Y.1711 [9]. This provides the same OAM concepts and methods (e.g. connectivity verification, alarm suppression, remote defect indication) already available in other transport networks, without requiring complex IP data plane capabilities. Ongoing standardization initiatives focus on G.8113 [10] and G.8114 [11].

In this HIPT project, both point-to-point and point-to-multipoint OAM will be considered to run within our Carrier Ethernet network to support the carrier-class network survivability.

MPLS TP therefore defines its protection capability using ITU-T G.8121/Y.1382 [12] and G.8132/Y.1382 [13]. MPLS fast ReRoute Network survivability traditionally deals with connection recovery after infrastructure or equipment failures, e.g. cable cuts or node outages, which are characterized by loss of signal. In addition to these “hard failures”, users of IPTV may experience signal quality degradation as a “soft failure”, caused by gradual component degrading or malfunction. Since the customers’ perception of the signal quality is critical for the successfulness of IPTV, survivability measures related to “soft failure” will be investigated in HIPT project. Accordingly in this test bed, the Carrier Ethernet access switches inside the Carrier Ethernet clouds supports the carrier-class OAM and protection. A set of failure scenarios could be set up to measure the reaction time within the carrier-class in order to improve the experience of services. Furthermore, multicast IPTV services with survivability will also be test within this test bed.

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